DEVELOPMENT AND EVALUATION OF ADVANCED TRAVELER INFORMATION SYSTEM (ATIS) USING VEHICLE-TO-VEHICLE (V2V) COMMUNICATION SYSTEM

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Hoe Kyoung Kim

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DEVELOPMENT AND EVALUATION OF ADVANCED TRAVELER INFORMATION SYSTEM (ATIS) USING VEHICLE-TO-VEHICLE (V2V) COMMUNICATION SYSTEM

Approved by:

Dr. Michael Hunter, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Michael Meyer
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Randall Guensler
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. John Leonard
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Richard Fujimoto
College of Computing
Georgia Institute of Technology

Date Approved: January 6, 2010

Dedicated to my parents

Byung Seok Kim and Imsoon Kim

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LIST OF ABBREVIATIONS

AAID	Autonomous Automatic Incident Detection Algorithm
ADVANCE	Advanced Driver and Vehicle Advisory Navigation ConcEpt
AID	Automatic Incident Detection Algorithm
API	Application Programming Interface
ATIS	Advanced Traveler Information System
ATMS	Advanced Transportation Management System3
CA	Cellular Automata
CDTA	Centralized Dynamic Traffic Assignment
COM	Component Object Model
DDTA	Decentralized Dynamic Traffic Assignment
DRGS	Dynamic Route Guidance System
DTA	Dynamic Traffic Assignment
GATIS-V2V	Georgia Advanced Traveler Information System Using Vehicle-to-Vehicle Communication System
GATIS-V2R	Georgia Advanced Traveler Information System Using Vehicle-to-Roadside Communication System
GPS	Global Positioning Systems
HDTA	Hybrid Dynamic Traffic Assignment
HLTT	Historical Link Travel Time
ITS	Intelligent Transportation System
IVC	Inter-Vehicle Communication

MAC	Media Access Control
MANET	Mobile Ad Hoc Network
MAPE	Mean Absolute Percent Error
O-D	Origin and Destination
PTV	Planung Transport Verkehr
RMSE	Root Mean Square Error
RT-ATIS	Real Time Advanced Traveler Information System
STM	Space-Time Memory
TMC	Traffic Management Center
TTI	Texas Transportation Institute
V2V	Vehicle-to-Vehicle Communication
V2R	Vehicle-to-Roadside Communication
VANET	Vehicular Ad Hoc Network
VII	Vehicle Infrastructure Integration
VISSIM	Verkehr In Staedten SIMulation (traffic in towns – simulation)
VMS	Variable Message Sign
WAVE	Wireless Access in Vehicular Environments

SUMMARY

This research develops and evaluates an Advanced Traveler Information System (ATIS) model using a Vehicle-to-Vehicle (V2V) communication system (referred to as the GATIS-V2V model) with the off-the-shelf microscopic simulation model, VISSIM. The GATIS-V2V model is tested on notional small traffic networks (non-signalized and signalized) and a 6X6 typical urban grid network (signalized traffic network). The GATIS-V2V model consists of three key modules: vehicle communication, on-board travel time database management, and a Dynamic Route Guidance System (DRGS). In addition, the system performance has been enhanced by applying three complementary functions: Autonomous Automatic Incident Detection (AAID), a minimum sample size algorithm, and a simple driver behavior model. To select appropriate parameter ranges for the complementary functions a sensitivity analysis has been conducted. The GATIS-V2V performance has been investigated relative to three underlying system parameters: traffic flow, communication radio range, and penetration ratio of participating vehicles. Lastly, the enhanced GATIS-V2V model is compared with the centralized traffic information system.

This research found that the enhanced GATIS-V2V model outperforms the basic model in terms of travel time savings and produces more consistent and robust system output under non-recurrent traffic states (i.e., traffic incident) in the simple traffic network. This research also identified that the traffic incident detection time and driver's route choice rule are the most crucial factors influencing the system performance. As expected, as traffic flow and penetration ratio increase, the system becomes more

efficient, with non-participating vehicles also benefiting from the re-routing of participating vehicles. The communication radio ranges considered were found not to significantly influence system operations in the studied traffic network. Finally, it is found that the decentralized GATIS-V2V model has similar performance to the centralized model even under low flow, short radio range, and low penetration ratio cases. This implies that a dynamic infrastructure-based traffic information system could replace a fixed infrastructure-based traffic information system, allowing for considerable savings in fixed costs and ready expansion of the system off of the main network corridors.

CHAPTER 1 INTRODUCTION

1.1 Background

The continuing disparity between the growth in surface transportation travel demand and the relatively minor addition of travel capacity has resulted in increased regional roadway congestion, greater uncertainty in travel time estimates, and higher real or perceived costs in safety and productivity [1]. As traffic congestion and accidents become increasingly frequent significant increases in related social costs seem to be inevitable, so numerous policies and strategies have been introduced to tackle both congestion and safety problems. Addressing congestion through the construction of new infrastructure has become prohibitively costly as a single solution. Thus, over the past several decades, Intelligent Transportation Systems (ITS) have risen as a promising means to improve transportation safety and mobility and enhance productivity through the use of advanced information and communication technologies [2]. ITS attempts to maximize the efficiency and safety of the current traffic system by accurately monitoring traffic states, computing and executing optimal alternative traffic strategies and distributing up-to-date traffic information to drivers.

Recent trends have seen increasing wireless communication capabilities and affordability. This has led many to explore wireless ITS solutions such as Inter-Vehicle Communication (IVC) systems. Enabled by wireless communication with neighboring instrumented vehicles each vehicle in a traffic information system using IVC system may act as a real time traffic data collector (e.g., link travel time) as well as a traffic information provider and consumer. Such a traffic information system is expected not only to reduce travel times by allowing vehicles to select less congested paths [3, 4] but also to improve safety by immediately sharing potential safety-related information such as abnormal deceleration of leading vehicles, unexpected vehicle stoppages, pavement conditions, etc [5-7]. In addition, with vehicles acting as the deployment platform any where vehicles travel such a system may be readily utilized, providing for rapid and economical expansion beyond the urban freeway system. Thus, IVC-aided traffic information systems capable of dynamically providing the up-to-date traffic information to vehicles and helping them responsively adjust their routes or instantly avoiding downstream traffic hazard have significant development and benefit potential.

1.2 Research Motivations

Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS) are typical ITS applications. Such systems may already be found deployed and implemented in urban areas of numerous countries, such as: Advanced Driver and Vehicle Advisory Navigation ConcEpt (ADVANCE) project in America [8], CityRouter.net in Germany [9], and Road Traffic Information Center in Japan [10]. A prime feature of many of these systems is a Traffic Management Center (TMC), which houses many of the traffic monitoring activities and provides traffic information to the public. Such systems may be referred to as fixed infrastructure-based traffic information systems. Historically, such systems require significant inroad, roadside, and centralized equipment along with costly communications networks (e.g., Variable Message Signs

(VMS) linked to TMC, fiber networks connecting sensors, etc.). Due to the costs such systems have also tended to be concentrated on urban freeways and major arterial, with little application to much of the remaining urban arterial system or rural facilities.

With the recent advent of more advanced technologies, particularly wireless communication technology, more economical traffic information systems are becoming possible. Numerous researchers are exploring IVC systems, focusing on hardware and software development and testing [11-13], aiming to achieve more efficient and effective communications. Given these recent advances the opportunity now exists to evaluate the utilization of these resources from the traffic engineering perspective.

Prior to deployment and wide-scale implementation of IVC systems it is useful to develop a simulation test bed for performance testing and resource utilization optimization. Key to a successful simulation test bed is the accurate modeling of vehicle mobility and the resulting dynamic communication network. Prior to the advent of IVC systems, the transportation and communication fields were commonly treated as different and independent research areas. However, the synergetic integration of these two different fields should be accomplished to successfully implement a transportation application using IVC system.

1.3 Research Objectives

The primary objective of this research is to explore the characteristics of a Real-Time Advanced Traveler Information System (RT-ATIS) using Vehicle-to-Vehicle (V2V) communications through a test bed implementation utilizing an off-the-shelf microscopic simulation model, VISSIM.

Specific objectives are as follows.

- To develop a RT-ATIS in which individual vehicle data (i.e., travel time) is shared among system participants, allowing each participant to estimate their route performance.
- To develop an integrated modeling platform to test the developed RT-ATIS, leveraging an existing off-the-shelf microscopic simulation model (i.e., VISSIM) enhanced with the ability to model V2V communications.
- To gain an understanding of the RT-ATIS performance under varying system wide traffic demands, user participation levels (i.e., penetration ratios), and equipment constraints (i.e., communication radio range).
- To gain an understanding of system performance under non-recurrent traffic conditions, such as traffic incidents, through a consideration of measures that incorporate the performance (including reliability) of both participating and non-participating vehicles.
- To investigate the potential benefits of the developed RT-ATIS compared to a system consisting of currently available ATIS technology with no V2V communication capability.

1.4 Research Contributions

This research effort is expected to provide the following contributions:

- develop an RT-ATIS using V2V communications,
- provide guidance on the use and development of a RT-ATIS test bed utilizing existing off-the-shelf simulators,
- provide an understanding of the characteristics of the RT-ATIS using V2V communication with respect to three underlying system parameters: traffic flow, communication radio range, and penetration ratio,
- introduce system performance-enhancing functions and define their parameter values,
- and provide an understanding of the operational trade-offs between an ITS strategy using only vehicle communication and a fixed infrastructure-based traffic information system.

1.5 Dissertation Outline

Following the research introduction in Chapter 1, this research effort is structured as follows. Chapter 2 reviews the critical difference between the currently deployed and IVC-aided traffic information systems, research trends on IVC, the key modules and functions required for development of ATIS model using an IVC system, and the applicability of microscopic simulation model to IVC research. Chapter 3 discusses the pre-process and main process for the development of the RT-ATIS using an IVC system, including three core system modules and three system performance-enhancing complementary functions. Chapter 4 investigates the basic characteristics of the developed model including a comparison with two centralized traffic information systems in the non-signalized simple network. Chapter 5 explores the difference between the basic and advanced RT-ATIS model using an IVC system for the same simple roadway network and traffic scenarios as Chapter 4. Chapter 6 evaluates the advanced model on a simple signalized network, including two traffic incident scenarios and a sensitivity analysis with the performance-enhancing functions. Then, Chapters 7 and 8 employ a 6X6 typical urban grid network to observe more general features of the developed model including comparisons with the centralized traffic information system. Lastly, Chapter 9 describes the findings from this research effort and suggests the future research.

CHAPTER 2 LITERATURE REVIEW

As stated, the objective of this research is to develop the basic framework of a RT-ATIS using V2V communication system, enhanced with complementary functions, and evaluated on a notional traffic network using an off-the-shelf microscopic simulation model. Then, the developed model (Georgia ATIS using V2V communication system - GATIS-V2V model) will be compared with a centralized traffic information system. This research effort contributes to ITS knowledge as preceding studies tended to be more focused on specific research topics opposed to comprehensive system development. The first step in the realization of this objective is to review underlying background knowledge and assess relevant studies on ATIS using V2V communication system.

2.1 Chapter Organization

This chapter begins with an introduction to the types and characteristics of traffic information systems in Section 2.2., followed by a description of the fundamental tasks required to develop the GATIS-V2V model in Section 2.3. Section 2.4 addresses the system-enhancing functions, and Section 2.5 reviews traffic simulation models.

2.2 Traffic Information System

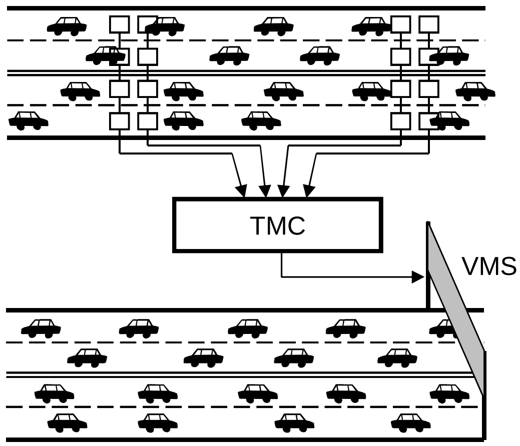
ITS encompasses a broad range of wireless and wire line communication-based information and advanced technologies integrated into the transportation system infrastructure and on board vehicles with the objective of relieving traffic congestion, improving safety, and enhancing traffic network productivity. ITS is made up of 16 types of technology-based systems divided into intelligent infrastructure systems and intelligent vehicle systems [2]. ATMS and ATIS are typical ITS applications that can be implemented to improve traffic network efficiency and safety in the urban area. Such systems are supported by sophisticated technologies such as vehicle detectors, Global Positioning Systems (GPS), communication devices, and roadside or in-vehicle visual display devices.

ATIS application deployments may be considered in two broad categories: fixed (typically with centralized control) and dynamic infrastructure-based traffic information systems. These systems are defined according to the mobility of physical infrastructure relaying the collected and processed traffic data. The former system collects and processes ATIS data (i.e., on-line and real-time traffic data) from fixed traffic detectors or probe vehicles, computes traffic management strategies corresponding to the prevailing traffic states, and provides drivers with the processed up-to-date traffic state information (normally descriptive traffic information) via several media such as cellular phones, Internet, variable message sign (VMS), or radio broadcasts. On the other hand, the latter system is based on direct data sharing with neighboring participating vehicles via wireless vehicle communication without relying on fixed infrastructure or centralized processing. In such a system individual participating vehicles act as real time traffic data collectors and processors, as well as traffic information providers and consumers (normally prescriptive traffic information) [3]. Table 1 shows that the mobility of the data collection points, scope of beneficiary, and source of construction and operation cost are the important factors in discerning an ATIS system as fixed or dynamic infrastructure-based traffic information systems. While defined above as two distinct categories, it is likely that an implemented ATIS will contain some aspects of each, resulting in a hybrid of the two approaches.

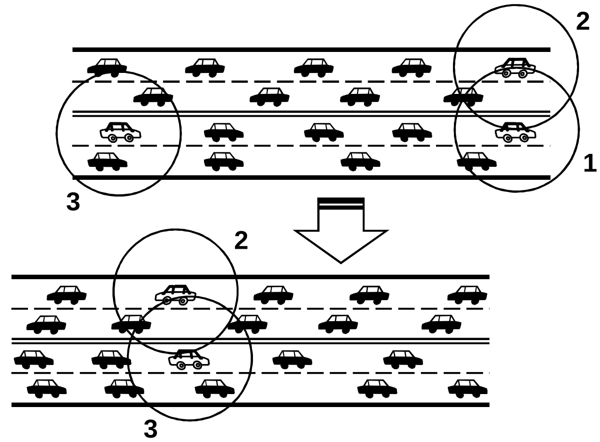
Table 1: Traffic Information System Definition with Required Infrastructure Type

Category	Fixed infrastructure system	Dynamic infrastructure system
Infrastructure	Facility-based	Vehicle-based
Data source	Passive detectors	Instrumented vehicles
Coverage	Designated location	Anywhere visited
Data dissemination	Open access	Subscriber-based
Cost model	Public funding	Public funding + private subscribers

Figure 1 illustrates operational examples of these two types of traffic information systems. In Figure 1 (a) the ATIS detector data is sent to the TMC for processing (i.e., fusion, screening, imputation, estimation, prediction, etc.) [1, 14] and traffic information is displayed by VMS. In Figure 1 (b) a dynamic system is illustrated, by highlighting the potential interaction between three instrumented vehicles. In this example westbound participating Vehicle 2 obtains the eastbound upstream traffic information (e.g., travel time of eastbound link) from Vehicle 1, as Vehicle 1 has just completed travel through that segment. In the near future Vehicle 3 becomes informed of the eastbound downstream traffic condition (i.e., the upstream experience of Vehicle 1) from Vehicle 2. Thus, through vehicle-to-vehicle communication Vehicle 3 has an opportunity to respond to the expected downstream traffic condition through route or lane changes, as appropriate.



(a) Fixed infrastructure-based traffic information system



(b) Dynamic infrastructure-based traffic information system

Figure 1: Example of Traffic Information System Operation

Note: TMC = traffic management center / VMS = variable message sign / white vehicle = participating vehicle / black vehicle = non-participating vehicle / circle = communication radio range (not the actual size of range)

2.3 ATIS Model Using V2V Communication

This research considers that the most fundamental and important components in developing and implementing an ATIS model using a V2V communication system are the vehicle communication, an efficient on-board database management strategy, and a dynamic route guidance system.

2.3.1 Vehicle Communication

A variety of communication-related factors affect communication performance. For example, the mobility of participating vehicles, the actual propagation behavior of an emitted signal, efficient routing protocols to identify and establish communication links with neighboring participating vehicles, and effective access control of the limited communication channel of individual instrumented vehicles are fundamental issues in implementing ATIS using V2V communication system. Each of these issues is discussed briefly in the following.

A) Mobile Ad Hoc Network (MANET) and Vehicular Ad Hoc Network (VANET)

A self-organizing and adaptive collection of communication nodes connected with wireless links is referred to as an Ad Hoc network [15]. If nodes are mobile, the network is termed as a Mobile Ad Hoc Network (MANET) [16]. In a multi-hop implementation data (i.e., packets) from the source can travel through intermediate nodes before reaching the destination [17]. A Vehicular Ad Hoc Network (VANET) is a class of MANET. A VANET is a distributed, self-organizing communication network in which the nodes are vehicles, and is thus characterized by very high node mobility and limited degrees of freedom in the mobility patterns. Such particular features often make standard MANET networking protocols inefficient or unusable in the VANET environment, leading to the growing efforts in the development of communication protocols specific to vehicular communication networks [18].

B) Mobility Model

A key factor that impacts the performance of V2V communication systems is the vehicle mobility patterns, in particular, in the urban street environment. The use of a mobility model that does not reflect the constraints of transportation applications, such as the random waypoint model, used in popular wireless communication simulators such as NS-2, OPNET and QualNet, can lead to erroneous results because they ignore the aspects of vehicular traffic such as vehicle acceleration and deceleration, queuing at signalized intersections and traffic congestion [19, 20].

C) Propagation Model

One of the challenges in wireless networks is signal attenuation. Communication results obtained without accounting for the impact of large obstacles, such as buildings, on the radio signal propagation areas likely provide unrealistic results [21-23]. Communication simulators typically model signal propagation with either the free-space model or a two-ray ground reflection model to predict the received signal power of each packet [24, 25], implying overly simplistic urban areas [22].

D) Routing Protocol

The high vehicle mobility in V2V communication systems lead to a continuously changing communication network topology and short connection times. Thus, V2V communication system routing protocols can incur high latency due to configuration time with uncoordinated vehicles. Reactive (or on-demand routing) schemes establish routes only when they are needed to send packets to a destination [26]. These protocols do so without periodical routing updates, however, it may be expected that initial packet delay will be higher due to the route discovery mechanisms. Proactive (or table-driven) schemes continuously maintain up-to-date routes for all valid destinations and require periodic updates to reflect network topology changes. In such an approach a large part of the available bandwidth is consumed by the routing mechanism. However, there is no latency to set up routes as in reactive routing protocols, although, routing convergence delay exists since routing information is periodically sent from neighboring nodes [27, 28].

E) IEEE 802.11 Media Access Control (MAC) Protocol

Since wireless communication is a tightly controlled medium, it has limited channel bandwidth, typically much less than that of wired networks. An efficient access control mechanism must coordinate the use of this shared resource. The IEEE 802.11 MAC protocol is current de facto standard for wireless links [16, 29].

F) Related V2V Communication System Research

Recently, much of the V2V communication research has been focused on proposing, developing, and evaluating effective and efficient communication protocols. Also, as the communication nodes are moving in the traffic network with high speed interactions with surrounding vehicles, significant research has been dedicated to studying the effect of transportation-related factors on the communication performance.

Xu and Barth [30] investigated a data transmission interval for optimizing V2V communication and they concluded that as the maximum transmission range varies, the minimum transmission interval should be adjusted from 0.2 second to 1.5 second to maintain the successfully received rate of a packet as at least 0.8. Wischhof et al. [31] also found that the adaptive transmission interval depending on the traffic condition outperforms the static transmission interval in reducing the packet collision. Michael and Nakagawa [32] evaluated the communication performance of single-hop and multi-hop data communication in terms of the amount of received information for a given communication radio range and they found that communication radio range is a function of transmitter power, receiver sensitivity and type of wireless transmission media (microwave, infra-red and so on) and multi-hop always delivers more information than single-hop communication. Most of these efforts were conducted using simulation method.

Hui [33], Aziz [34], Gupta [35], and Jerbi [36] performed experimental tests with specially designed communication equipment or instrumented vehicles to gain better insights into the relationship between communication parameters and performance. They found that packet loss is much higher in vehicular communication than in the static communication scenario. Furthermore, communication throughput degrades with the number of hops traversed. A general finding from these efforts is that traffic information systems using V2V communication to achieve the maximum performance under heavy traffic demand conditions by transmitting and receiving bulky traffic information through multi-hop communication require more robust communication algorithms and protocols adaptable to various communication environments. These protocols should be capable of better handling vehicular communication characteristics to allow for more effective implementations of transportation applications.

Other researchers focused on the effect of transportation-related parameters (e.g., traffic congestion level, traffic density, traffic geometries, vehicle speed, penetration ratio, etc.) on communication performance (i.e., vehicle communication connectivity and temporal and spatial data propagation) using simulation and analytical methods. Wu [37, 38], Schonhof [39], Kato [40], and Jin [41] found that traffic density, penetration ratio, vehicle speed, and relative speed are important factors influencing the efficiency and velocity of information propagation. These findings have been obtained from the freeway experiments with the simulation method.

Artimy [42], Chen [43], and Yang [44] concentrated more on roadway geometry and concluded that weak node connectivity within one driving direction can be overcome by the inclusion in the communication hops of vehicles traveling in the opposing direction, that multi-lane traffic within the same direction improve end-to-end transmission delay, and that the bandwidth/data rate requirements for participating vehicles in an urban arterial streets environment are relatively higher than that of freeway networks due to the complex network configuration and high density of vehicles distributed within the two-dimensional space.

2.3.2 On-board Database Management Strategy

Most TMCs using fixed location real-time ITS data (i.e., loops, radar, passive acoustic, video detectors, etc.) as the main data source are suffering from temporal and spatial data coverage problems. For example, research on the quality of loop detector data reported that 20 to 30 % of the volume and speed data are unavailable or erroneous [45-49], requiring intensive studies on filtering and imputation of erroneous and missing data.

While outages and inaccuracies tend to be the primary challenges regarding fixed infrastructure based traffic data ATIS using V2V communication face a different set of data challenges. The data tends to be sparse (i.e., only a small subset of all vehicles is instrumented), data is transmitted from a high number of sources potentially placing high demands on the communication infrastructure, data from multiple sources regarding the same roadway must be aggregated, and roadways may have no or intermittent data coverage, depending on the presence of instrumented vehicles. The following is a review of research on data treatment in ATIS using V2V communication.

Given the sparse nature of the data the traffic state information (i.e., travel time) for all vehicles will not be available. Xu et al. [4] suggested three travel time estimation techniques with travel time collected from IVC vehicles, using an augmented simulation model with PARAMICS and NS-2 on the freeway of interest. They compared the simulated individual travel time data with aggregated simulated results on one link based on Mean Absolute Percent Error (MAPE) and found that the travel time estimation method can have a dramatic effect on overall system performance, primarily in the accuracy of true travel times. This effort did not consider a means for travel time estimation where current IVC data was not available. It also did not consider the urban arterial network.

Nadeem et al. [50, 51] developed a framework to disseminate and gather information about the position and speed of vehicles on the road, named TrafficView. Since the size of data sent and received by individual instrumented vehicles are restricted by the capability of the current wireless technology, it is necessary to aggregate the traffic data to reduce the message size necessary for data communication. Their proposed data aggregation algorithm is to generate one record from several vehicles within close proximity and moving with relatively same speed to deliver as many records as possible in one broadcast message. They measured the performance of the data aggregation and the simple data propagation method in terms of vehicle visibility and the average error in estimating the position of vehicles in front of each vehicle and found that the effect of the data aggregation is more significant compared to the simple data propagation.

Yang et al. [52] introduced a modified exponential filter incorporated in each instrumented vehicle for their dynamic on-line routing behavior model, to smooth estimates of link travel time as new raw link travel time data are received. Smoothing factors in modified exponential filters are dynamically calculated based on differences between the time stamp of the most recent packet to be used in this smoothing cycle and the time stamp of the packet last stored for the same link.

In summary, in order to manage and represent the temporal and spatial traffic state information and facilitate more efficient data communication under the current communication restriction various traffic data aggregation and estimation methods have been introduced. From these efforts it is clear that the quality and quantity of traffic data managed in the on-board database and transmitted between neighboring participating vehicles are crucial in implementing the traffic information system using V2V communication.

2.3.3. Dynamic Route Guidance System (DRGS)

DRGS is considered as one of the most applicable and demanding ITS applications. Seminal research on this topic has been conducted, but many interesting and unanswered issues remain. For example, dynamic route guidance algorithm development [53], driver's route choice behavior (i.e., compliance ratio), driver's route preference [54], and relocation of traffic congestion are areas where meaningful contributions are still needed.

Recently, many research efforts have been made to investigate effectiveness of DRGS in the traffic information system using V2V communication. Lee, J. et al. [55, 56] developed a simulation test bed using VISSIM and VISSIM COM to explore applications of the Vehicle Infrastructure Integration (VII) initiative to DRGS by evaluating various route guidance strategies with V2R communication. They evaluated unguided traffic condition and four guided traffic conditions with diverse variables such as different type of route guidance method, penetration ratio, congestion level, updated interval, and driver compliance ratio. They concluded that VII-based route guidance has superiority in reducing travel time to unguided traffic condition.

Yang et al. [52] developed a simulation framework using PARAMICS to explore the potential benefits from dynamic vehicle on-line routing utilizing dynamic infrastructure-based traffic information on freeway and urban arterial networks. They reported that IVC-capable vehicles can make sufficiently accurate estimations of real-time traffic conditions to take effective re-routing actions.

Krajzewicz et al. [57] evaluated if IVC systems can reduce traffic jams or it simply relocate jams by re-routing the vehicles. They extended an existing microscopic simulation model (i.e., SUMO) by embedding IVC capabilities. They found that increasing the percentage of instrumented vehicles reduces the measured mean travel time and even non-instrumented vehicles benefit from re-routing of instrumented vehicles. When significant percentages of vehicles re-route system efficiency decreases, however, travel time savings still exist. Liu et al. [58] also stressed that 100% communication does not yield the best result in terms of throughput because all vehicles will choose the secondary route to avoid the congested route, leading to congestion in the secondary route and reduce the system throughput.

Laborczi et al. [59] explored the disadvantages of the fixed and dynamic infrastructure-based systems and developed a novel hybrid network architecture taking advantage of both systems using an integrated simulation model of VISSIM and NS-2. They evaluated average travel time by route by applying route guidance strategies to several system architecture such as traditional, fixed infrastructure-base, dynamic infrastructure-based, and hybrid systems. They showed that hybrid system provides less travel times and less congested roads.

In summary, DRGS in the traveler information system using V2V communication is distinct from that employed in the centralized traffic information system in that individual participating vehicles autonomously collect, share, and update traffic data and search for the more time-efficient route. Many simulation models have been developed to investigate this unique traveler information system. DRGS using V2V communication has been shown to improve traffic mobility, however, some inefficient cases when the penetration ratio reaches 100% have be identified, where the autonomous and independent route-searching method result is sub-optimal performance.

2.4 System Performance-enhancing Functions

Significant research has been dedicated to improving the efficiency of ATIS and the development of more reliable and realistic ATIS models. These research efforts have predominately centered on ATIS applications using fixed infrastructure-based traffic information. This current research effort attempts to incorporate many of these proposed efficiency improvements into an autonomous decentralized traffic information system (i.e., individual participating vehicles). The utilized functions are automatic incident detection algorithm, incorporation of probe vehicle sample size considerations, and a drivers' route choice model.

2.4.1 Automatic Incident Detection (AID) Algorithms

A traffic incident is an unexpected and non-recurrent traffic state and a response should be pursued to minimize its adverse impact [60]. Numerous strategies for early detection of traffic incidents have been developed, evaluated, and deployed in ATMS implementations [60-62]. However, since most AID algorithms implemented in TMCs rely primarily on the fixed sensor data, traffic engineers and practitioners have strived to minimize inherent system errors such as false alarms caused by inaccurate data.

AID algorithms are usually classified into one of five major categories depending on the data source: roadway-based algorithms, probe-based algorithms, driver-based algorithms, sensor fusion-based algorithms, and arterial-applicable algorithms [60, 63, 64]. Focusing on ATIS applications using V2V communication, Table 2 describes the operational features of the probe-based incident detection algorithms studied in the U.S. Most of these are limited to freeway incident detection, except the ADVANCE model which incorporates the urban arterial network. Incident detection for the signalized streets has received significant attention from traffic operations and control personnel only in recent years [63]. Particularly, Thomas and Hafeez [65] did a simulation study using a modified INTRAS (i.e., Integrated Traffic Simulation package) for AID system calibration within the framework of ATIS and ATMS in the fixed infrastructure-based traffic information mode on a signalized arterial with travel time collected from probe vehicles. They found that detection of the clearance of an incident, as well as the start of an incident, is very important element in calibrating the AID system in the signalized arterial network. Also, Yang and Recker [66] developed and implemented a self-organizing distributed traffic information system in the dynamic infrastructure-based traffic information mode with PARAMIC and its APIs. They included an AID function in the individual participating vehicles and they issued an incident alert when the experienced or transmitted travel time data is over the historical link travel time of interest on a freeway, signalized arterials were not included.

Table 2: Operational Features of the Probe-based Incident Detection Algorithms [63]

Algorithm name		Probe sensor technology	Penetration ratio	Traffic environment	Experiment type	Data requirement	Detection interval
MIT	Headways algorithm	AVI/ETC	50%	Freeway	MITSIM-based simulation	Travel time and headway by lane	≈0.8 min
	Lane switches algorithm					Lane switches	
	Lane-monitoring algorithm					Volumes by lane	
ADVANCE	Travel time algorithm	GPS or AVI	30 or fewer probe reports per interval	Arterial	INTRAS-based simulation	Travel time	7 min
	Dynamic measures algorithm	GPS and map matching	1 probe per interval		Field in the suburbs of Chicago, IL	Total travel time, running time, and 1-sec position	N/A
TTI		Cellular probe system	5-min headway	Freeway	Field in Houston, TX	Travel time	15 min
UCB		CDPD radio	7-min headway	Freeway	Field in Hayward, CA	Speed and acceleration	0.5 min
TRANSMIT		AVI/ETC	1-min headway	Freeway	Field in metropolitan NYC	Travel time	15 min
Waterloo	Speed and confidence limit algorithm	AVI/ETC	10%	Freeway	INTEGRATION-based simulation	Travel time	≈0.3 min
	Dual confidence limit algorithm						
	Dual confidence limit algorithm						

2.4.2 Probe Vehicle Sample Size Study

When incorporating sample size an ATIS model using travel time data collected using instrumented vehicles (i.e., probe vehicles) is required to secure a minimum number of network monitoring vehicles for reliable travel time estimation [67, 68]. The ADVANCE project conducted in Chicago in the early to mid 1990s is the typical example of an ATIS model using travel time data collected and transmitted from probe vehicles through road side communication equipments to a centralized and fixed infrastructure-based traffic information system [69, 70]. Guhnemann et al. [71] introduced another centralized ATIS application using real time traffic data collected from GPS-equipped taxis in Germany, for real-time traffic jam detection and dynamic routing and navigation tools.

Srinivasan and Jovanis [67] proposed a general heuristic algorithm for estimating the number of probe vehicles required in a network for reliable travel time estimation and tested it using a 2-hour peak period simulation model of the Sacramento network. They found that the time period for travel time estimation, the number of replications of travel time desired for each link during each measurement period, the proportion of links to be covered, and the length of the peak period are important factors in determining the probe vehicle sample size. Less than 5% of the total peak period volume could reliably cover 80% of major arterials and freeway links, although probe vehicles can’t be used as a single traffic data source during off-peak periods and on a lightly traveled corridors and low-speed road.

Chen and Chien [72] suggested another heuristic method for determining the minimum number of probe vehicles required with simulation output (i.e., CORSIM) on the section of I-80 in New Jersey. They found that the common assumption that link travel time is normally distributed does not hold in some cases and that the geometric condition and traffic volume are factors affecting the vehicle travel time distribution.

Unlike probe vehicle sample size studies conducted along the freeway or main arterials, Alexandre [73], Graves at el. [74], and He [75] investigated the effect of traffic signals on the travel time variability on the signalized urban network. They found that link travel time and link arrival time has a significant correlation. Furthermore, differentiation of link travel time according to the upstream and downstream traffic signal phases would increase the accuracy of travel time estimation but require additional observation time to secure the required sample size. It is noted that no studies on the effect of roadside activities from driveways, parking lots, loading and unloading, etc., on the probe vehicle sample size were found in the literature.

In the currently proposed system individual instrumented vehicles in the decentralized and dynamic infrastructure-based traffic information system store and update travel time data in their own on-board database by experiencing or receiving information from neighboring vehicles. In some sense each vehicle may be treated as mobile TMC. Intuitively, unless a communication group consisting of participating vehicles in the dynamic infrastructure-based traffic information system covers the entire traffic network, the amount of traffic data managed in individual participating vehicles would be less than the centralized traffic information system. However, considering the beacon density and system scalability issues in the centralized system the decentralized system might have more advantages over the centralized one.

2.4.3 Driver Behavior Model

ATIS is increasingly being recognized as a potential strategy for influencing driver behavior regarding route choice, trip making, time of departure, and mode choices. The provision of real-time travel information allows travelers to make informed travel decisions and has the potential to improve network efficiency, reduce congestion, and enhance environmental quality. The successful implementation of these systems, however, will depend to a large extent on understanding how drivers adjust their travel behavior in response to the information received [76]. Accordingly, numerous research efforts have been made to investigate influence of ATIS data on drivers' route choice behavior and vice versa. Chen and Jovanis [77] and Srinivasan and Mahmassani [78] found that drivers' compliance with the guided route may be affected by information accuracy, conveyance method, network familiarity, traffic incident occurrence, etc.

Chen and Mahmassani [79-81] proposed a boundedly-rational switching rule, stating that drivers change their route only if the improvement in the remaining trip time exceeds some indifference band of trip time saving. Simulation output indicated that an indifference band of 0.2 yielded reasonable overall behavior and the largest system-wide improvement in travel time. In addition, Ben-Akiva and Morikawa [82-84] conducted an empirical analysis of commuting route switching models with binary-logit choice model. They found that time and distance have significant roles as determinants of route choice and other attributes like scenic time (% of link length through scenic areas) and highway distance (% of link length on highway) are also demonstrated to contribute to the utility function of inter-urban route choice behavior.

In summary, several system performance-enhancing functions (i.e., automatic incident detection algorithm, minimum sample size of traffic data, and driver route choice rule) are introduced to improve the system efficiency and reliability. Implementation of automatic incident detection algorithm in a signalized arterial network, minimum sample size of traffic data whose distributions may not follow the normal distribution and gaining a thorough understanding of drivers' response to the processed traffic state information are drawing increasing attention. Each of these will be applied in the proposed autonomous decentralized traffic information system.

2.5 Traffic Simulation Model for ATIS Using V2V Communication

This research attempts to build and test an ATIS model that can model communication characteristics in urban areas using a widely accepted off-the-shelf transportation microscopic simulation model, rather than employing existing mobility models used in communication network simulators, by incorporating basic features of wireless vehicle communication into the microscopic traffic simulator.

2.5.1 Microscopic Simulation Model

To implement dynamic infrastructure-based traveler information systems with realistic communication node mobility a microscopic transportation simulation model should be employed. A microscopic simulation models individual vehicles (i.e., communication nodes) utilizing established traffic theory such as car-following and lane changing models

[85]. A variety of microscopic simulation tools such as PARAMICS, CORSIM, VISSIM, and so forth have been developed to analyze transportation scenarios. Even though microscopic simulation models require more computing resources than most macroscopic approaches recent improvement in computing systems enable its use in almost every transportation-related application. However, there has been little effort expended on integrating communication techniques and scenarios into a realistic transportation simulation environments [19].

In addition, recent microscopic simulation models tend to provide user interfaces (i.e., application programming interface (API)) from which a user can access and control objects in the traffic network at runtime. This interface makes it feasible for a user to elicit the necessary data from each vehicle, save the intended output periodically, change the vehicle movement rules, and even apply dynamic vehicle control. Thus, it is possible to realize the integrated communication simulation model with the commercial microscopic simulation model for the multiple purposes. Consequently, the popular commercial microscopic simulation model widely used in transportation field is a good means to simulate the dynamic infrastructure-based traffic information system.

2.5.2 Integrated Simulation Models

Simulation is not always a simple task because each instrumented vehicle acts as a mobile communication node on the traffic network at high speed, so the communication link established when two mobile communication nodes meet may quickly be broken due to the vehicle's moving out of range. Also, they self-organize to form a communication network without the need for infrastructure, so it is difficult to intentionally route another communication node within radio range [86, 87]. It is necessary to simulate vehicle movement, radio propagation, routing protocol and media access control (MAC) protocol behavior in the dynamic infrastructure-based traveler information system. Fortunately, microscopic traffic models, radio propagation models, and wireless system models are all currently available, but need to be combined and integrated with new and specific VANET protocols and respective applications [88]. Before dynamic infrastructure-based traffic information systems were introduced, transportation and communication fields were often treated as different and independent research areas. However, the synergetic integration of the two different fields should be accomplished to successfully implement a dynamic infrastructure-based traffic information system. Accordingly, seminal research has been conducted to overcome the addressed concerns by developing integrated simulation model with traffic mobility and wireless communication simulators.

Eichler et al. [88] developed a simulation model integrated with traffic simulator, CARISMA, and network simulator, NS2. They proposed four coupling methods to pursue the synchronized data exchange between them. Also, they plan to replace the traffic simulator with VISSIM due to its more detailed and realistic representation of vehicle mobility. Wu et al. [38, 89] used a federated approach to integrate a traffic simulator, CORSIM, and a network simulator, QualNet and tested their new data dissemination algorithm (MDDV, a Mobility-centric Data Dissemination algorithm intended for Vehicular networks) and analytical models for the spatial data propagation in VANET environment. Kim [3, 90] constructed a simulation framework for V2V communication with traffic simulator, PARAMICS, and network simulator, QualNet and used the integrated model as one component of a traffic information system. It, however, is very challenging to coordinate the individual simulators. For instance, since the location information of each instrumented vehicle in a vehicle mobility simulator should be transferred to communication network model, simulation time of both simulators should be synchronized. Interestingly, Krajzewicz et al. [57] added the communication module to the mobility simulation model (i.e., SUMO) and Yang [44] incorporated a simplified communication function into the traffic simulator, PARAMICS.

2.5.3 Newly Developed Simulation Models

Another research trend on implementation of V2V data communication with realistic node mobility is to create a new simulation model without relying on the access-limited commercial simulation models.

Widodo and Hasegawa [91] developed an autonomous traffic flow simulator including the V2V communication system to evaluate the effectiveness of the IVC system for improving the traffic safety with a conclusion that the IVC system can reduce the accident occurrence ratio. Artimy et al. [92] designed a lightweight microscopic traffic simulator (i.e., RoadSim) by extending an existing Cellular Automata (CA) system, and combined it with the compatible network simulator, NS2. Mangharam et al. [93] proposed a hybrid simulator (i.e., GrooveNet) which enables communication between simulated vehicles, real vehicles and between real and simulated vehicles. They conducted a field test with five vehicles running GrooveNet in the hybrid mode and it showed the reasonable communication performance.

Unlike other simulation models integrating existing mobility and communication simulators or newly created simulation models combining mobility and communication features, this research develops and implements a traveler information system using V2V communication by incorporating the communication capability into the off-the-shelf microscopic simulation model, VISSIM, under an ideal communication environment (i.e., no signal interference and no data loss for data communication). This research investigates the transportation system performance, rather than the communication performance.

2.6 Summary

ITS is a promising means to mitigate traffic congestion and improve traffic safety. The most common ITS platforms are fixed infrastructure-based and dynamic infrastructure-based traffic information system. The most critical differences between these are the mobility of the data collection points, scope of beneficiary, and source of construction and operating cost. The advanced traveler information system using V2V communication system could consist of three key system components: vehicle communication, on-board database management strategy, and dynamic route guidance. It has been seen that many researchers have found that both communication system and transportation factors affect the communication performance. Aggregation and estimation methods of on-board traffic database is also important element for the overall system performance, and most DRGS using V2V communication system improves the traffic mobility. In order to improve the system efficiency and reliability many traffic engineers and researchers implement and evaluate diverse complementary schemes like the automatic incident detection algorithms for the quick response to traffic incident, minimum sample size of the real-time traffic data, particularly, collected from probe vehicles, and realistic drivers' route choice model. Most research efforts on V2V communication system have been made with the simulation method due to limitation of complete physical system development and inability to secure sufficient market ratio of the instrumented vehicles. Therefore, integrating communication and traffic mobility models is prerequisite for implementing and evaluating the ITS models using V2V communication system. Some researchers develop their own simulation models capable of modeling the communication and vehicle mobility together.

However, most system components and complementary schemes have been partially studied and investigated mainly in the freeway network, so a comprehensive ATIS model using V2V communication including all aforementioned functions needs to be developed and tested in relatively complicated signalized traffic network. Focusing on the system efficiency and performance from the transportation perspective, the off-the-shelf microscopic simulation model emulating the simple and ideal communication conditions can be constructed as the test bed of the developed model.

CHAPTER 3 DEVELOPMENT OF GATIS-V2V Model

This chapter discusses the development and implementation of the GATIS-V2V model with the off-the-shelf microscopic simulation model and its extension, VISSIM and VISSIM COM, respectively. Prior to the main development process of GATIS-V2V model, numerous pre-conditions and pre-processes are addressed.

3.1 Conceptual System Architecture of GATIS-V2V Model

Figure 2 depicts two separate processes in the conceptual architecture of the GATIS-V2V model. Pre-process includes the operational process and the initialization data process: the former deals with the multiple technical subroutines devised in this research that provide rules for vehicle turning movement, link travel time definition, define the in-vehicle database structure, provide for dynamic management of the computing resources, define vehicle priority and traffic incident realization, and provide communication data packet size information. The initialization data process handles the generation of data files to be used as input data to the main process. The main process includes several modules that comprise the main components of the GATIS-V2V model: vehicle communication, on-board database management strategy, and DRGS. The vehicle communication module forms communication groups of adjacent participating vehicles located within the communication radio range and handles traffic data dissemination in the individual communication groups, the on-board data base management strategy updates and estimates the traffic state on each vehicle every pre-determined time interval and the DRGS searches for the most time-efficient path based on the up-to-date traffic states. Most processes developed are realized and verified in the 6X6 urban grid traffic network.

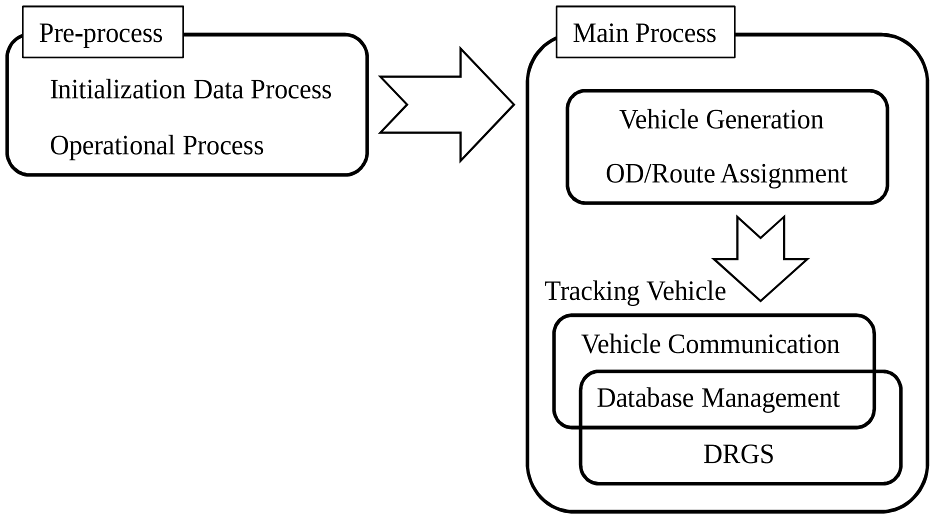


Figure 2: Conceptual GATIS-V2V Architecture

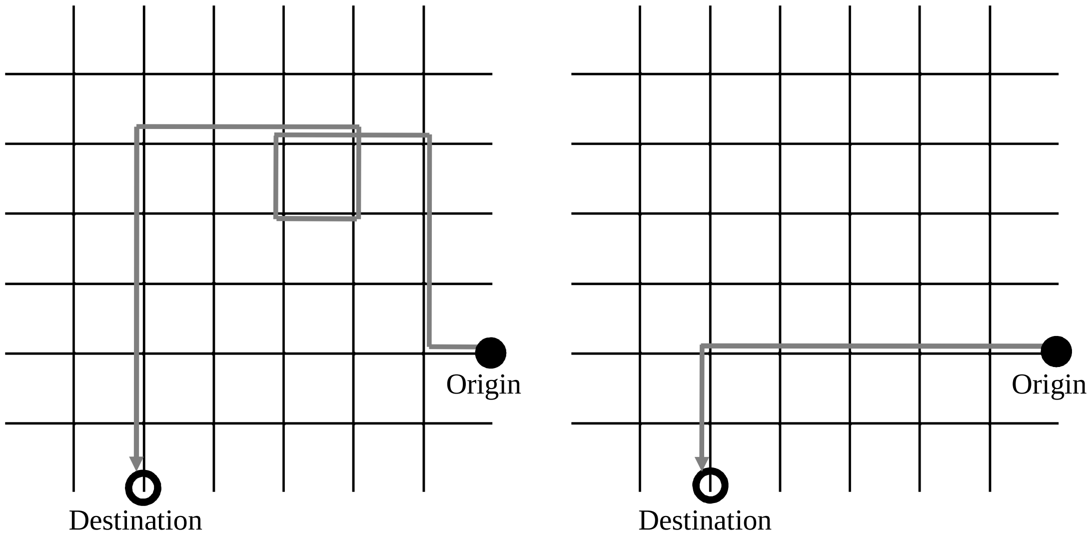
3.2 Pre-process of GATIS-V2V Model

3.2.1 Operational Process

The operational processes define underlying modeling constructs that must be determined as part of the development and testing of the GATIS-V2V model. Included within the operational processes is the defining of the rules that will be used for vehicle route selection, outlining travel time data collection and aggregation methods, managing arrays and databases, setting communication protocols and assumptions, etc. Each of these is discussed in detail in the following sections.

A) Conditional turning movement

To test the GATIS-V2V model all vehicles are initially assigned origin and destination points at random. While not optimized it is assumed that initial vehicle paths from the origins to destinations are rational. That is, the GATIS-V2V model manages the number of possible routes from the specified origin to the destination by requiring all vehicles to avoid any cycles within their path and assumes there are no mid-path stops. Also, a vehicle will not select a movement (left, through, or straight) that results in the vehicle increasing the Euclidian distance to the destination point. It is recognized that the ability to utilize this constraint is unique to the Manhattan style grid utilized for the experiments in the research and future efforts on more realistic networks will need to relax this constraint. Figure 3 illustrates turning movements of a vehicle as would be allowed by VISSIM in an uncontrolled environment and as in the GATIS-V2V model. These path selection rules are utilized in DRGS as well. In the GATIS-V2V model not all vehicles will utilize the same path between an origin-destination pair, instead being randomly assigned to the subset of possible paths that meet the defined routing conditions; this will be explained later in greater detail.



(a) General turning movements in VISSIM model

(b) Conditional turning movements in GATIS-V2V model

Figure 3: Turning Movement Comparison between VISSIM and GATIS-V2V Models

B) <u>Link travel time</u>

The travel time of a vehicle across a link varies depending on traffic signal timing parameters (i.e., cycle length, offset, signal phase, and phase sequence) at the link boundary intersections and the upstream arrival from, and downstream departure to, intersections of the subject vehicle. Nine different possible paths through two consecutive intersections may be identified by pairing turning activities conducted at the upstream and downstream intersections (black solid and dotted arrows in Figure 4). However, this research tracks the travel time for only five different paths (black solid arrows in Figure 4), following the aforementioned conditional turning movement rule (e.g., a vehicle would not turn left on to and then left off a link) and taking into account that travel time corresponding to a right turn at the downstream intersection would be similar to that of through movement (i.e., assumes no, or at least limited, right on red movements). For instance, 6X6 urban gird traffic network generates 720 link travel paths.

Upstream → Downstream left turn

Upstream → Downstream through

Upstream → Downstream right turn

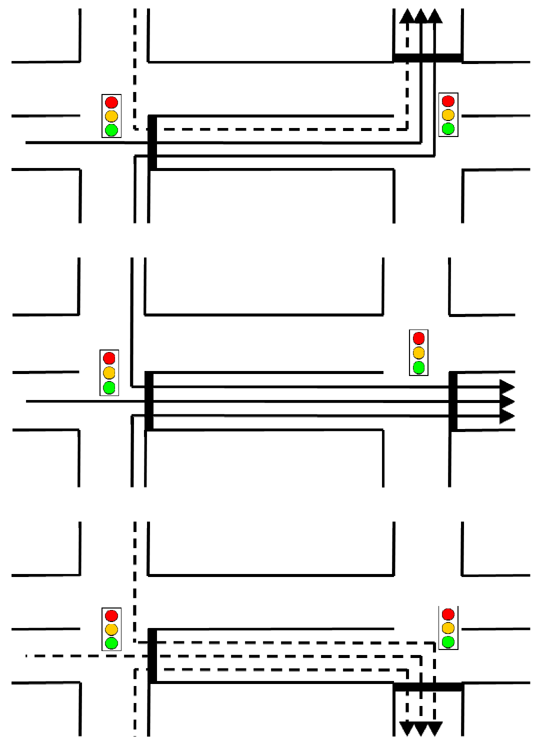


Figure 4: Disaggregated Link Travel Times for One Link

C) Vehicle turning control methodology in the GATIS-V2V model

As stated the GATIS-V2V model is currently implemented using the VISSIM microscopic simulation model, thus the vehicle routing is implemented using VISSIM techniques. At the time of vehicle generation in the GATIS-V2V model, their origin and destination and route (i.e., O-D/Route) are assigned. The route is represented as a list of links. The VISSIM *vehicle type* attribute is utilized to make the vehicle to follow their assigned route (i.e., link list) through the network. Each movement (left, through, and right) is assigned to a unique *vehicle type* (in VISSIM vehicles may be assigned as different types, e.g., car1, car2, etc.). Whenever a vehicle enters a new link the GATIS-V2V model assigns the vehicle type associated with that vehicle's route at the downstream intersection (Figure 5). This particular method offers the flexibility of updating vehicle routes during run-time by updating the routing link list maintained by the GATIS-V2V model.

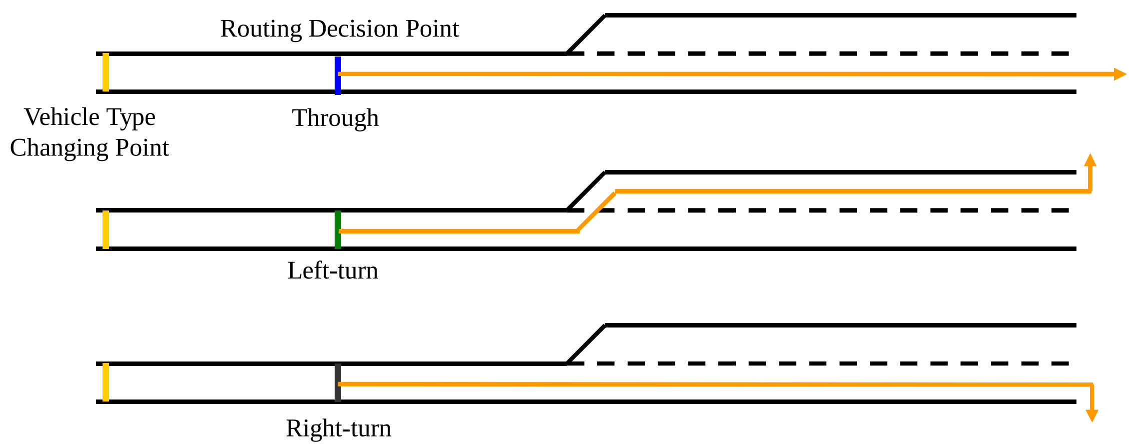


Figure 5: Vehicle Turning Control Methodology in GATIS-V2V Model

D) <u>Space-time memory definition</u>

The GATIS V2V model utilizes a space-time memory (STM) embedded in the on-board computer of participating vehicles. The STM consists of three dimensional lists: system update time interval, link number, and travel time records (travel time and vehicle ID) (Figure 6). While participating vehicles are traversing the network and communicating with neighboring participating vehicles, travel times (both experienced by the vehicle itself and received from other vehicles) are saved in the pertinent cell for the corresponding link number and time bin. An on-board computer performs the required processes to update the estimated link travel time, which is used for the DRGS. This database is flexibly resized according to the traffic network size.

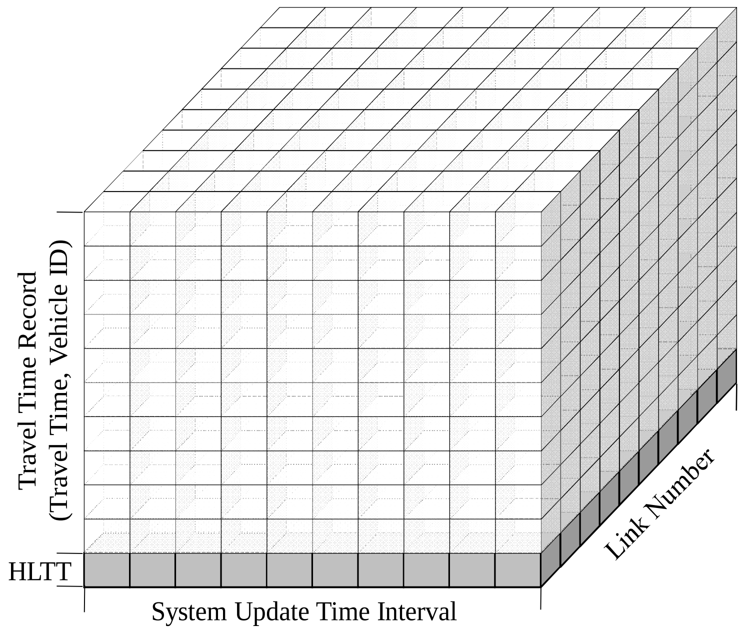


Figure 6: Space-time Memory (STM) in On-board Computer of Participating Vehicles

E) <u>Dynamic update of number of participating vehicles</u>

In conducting the GATIS V2V model experimental runs it was seen that the number of participating vehicles that could be included was limited by the available computer resources. The GATIS V2V model platform was enhanced to better utilize system resources. Computing resources (which are confined by a external programming environment, Visual Basic .NET in this research) restrict the memory size directly related to the number of participating vehicles and links, simulation time period, and amount of traffic data. Hence, efficient management of computer resources is required to investigate various scenarios for sufficiently long time periods. This study defines an on-board link travel time database using a four dimensional array *DB(vehicle number, link number, system update time interval, travel time record)* as data type "short integer" consuming 2 bytes per cell under Visual Studio .NET development environment. Each "*vehicle number*" in *DB* stands for the STM of individual participating vehicles.

The number of participating vehicles on a network is primarily dependent on the traffic demand and penetration ratio. In order to model an extreme case of 100% penetration ratio under the steady state traffic, this research effort develops an algorithm to maintain specially designed arrays recording and updating vehicle IDs entering and departing the network, instead of simply adding new vehicles to the database. Specifically, two arrays ($S(\,)$: vehicle ID array and $Q(\,)$: vehicle order array) record the vehicle ID of new participating vehicles and vehicle order of departing vehicles, respectively. These elements are utilized in determining the number of vehicles that must be tracked in the database. When participating vehicles depart the network, data in relevant array elements and databases are reset to reuse for new participating vehicles.

The algorithm is as follows:

$For\ t = 1\ to\ STP$

$\quad New\ Vehicle\ Generation$

$\quad\quad If\ M = m\ then$

$\quad\quad\quad i = i + 1$

$\quad\quad\quad S(i) = New\ Vehicle\ ID$

$\quad\quad\quad DB(i,\ links,\ times,\ data)$

$\quad\quad ElseIf\ M > m\ then$

$\quad\quad\quad m = m + 1$

$S(Q(m)) = New\ Vehicle\ ID$

$DB(Q(m),\ links,\ times,\ data)$

$EndIf$

$Vehicle\ Departure$

$S(x) = 0\ or\ S\big(Q(y)\big) = 0$

$DB(x,\ links,\ time,\ data) = 0\ or\ DB(Q(y),\ links,\ time,\ data) = 0$

$M = M + 1$

$Q(M) = x\ or\ Q(M) = Q(y)$

$Next\ t$

where:
t = time
STP = simulation time period
$S(\ )$ = vehicle ID array
$S(\#)$ = vehicle ID of #th vehicle
$Q(\ )$ = array of vehicle order in $S(\ )$
$Q(\#)$ = vehicle order of #th vehicle in $S(\ )$
M = number of departing vehicles
$m =$ number of generated vehicles replacing previous vehicle order in $S(\ )$

F) Dynamic update of system time interval

As will be seen in a later discussion (Section 3.3) of the GATIS-V2V model main processes the model utilizes the travel times over the past three time bins, as well as the completed portion of the current time bin to estimate and predict the short-term travel time for the next time bin. To efficiently utilize memory resources data from early time bins is not retained. When reaching the system update time interval (i.e., the end of a time bin) the GATIS-V2V model deletes the data in the oldest time bin and moves other data to the past by one time interval.

The algorithm is as follows:

$$DB(VehID,\ links,\ 1,\ data) = 0$$

$$For\ T = 1\ to\ 3$$

$$DB(VehID,\ links,\ T,\ data) = DB(VehID,\ links,\ T+1,\ data)$$

$$DB(VehID,\ links,\ T+1,\ data) = 0$$

$$Next\ T$$

where:
T = time ID

G) Communication data packet size

This research uses omni-directional broadcasting with flooding as the data dissemination scheme. Data are disseminated by multi-hop among neighboring participating vehicles within individual communication groups.

Table 3 contains data packet size for one cell in the STM. This research assumes to adopt IEEE 802.11p or the Wireless Access in Vehicular Environments (WAVE) communication standard for facilitating low latency, high data rate (i.e., 27Mbps), and high mobility communications [94, 95]. Thus, even when the travel time database on the on-board computer in a participating vehicle is large, data dissemination via the GATIS-V2V model would be executed almost instantaneously, even in large communication groups. For instance, the travel time database of one participating vehicle in 6X6 urban grid network consists of 720 travel time links, 4 dynamically updated time bins, and 30 vertical data spaces (i.e., biggest minimum sample size for 500vph case as will be seen in Section 3.5.2). This database has a maximum data size of 4.8Mbps (= 720 * 4 * 30 * 7 bytes), requiring less than 0.18 seconds for data dissemination under the ideal communication environment (i.e., no routing time, no signal interference, no data loss during the multi-hop communication).

Table 3: Data Packet Configuration

Category	Data size	Description
Vehicle ID	2 bytes	Unique vehicle ID number of participating vehicle
Link ID	2 bytes	Link information considering link separation
Time ID	1 byte	Dynamically updated time information
Travel time	2 bytes	Time difference between two consecutive link entering times

H) Vehicle priority rule application (conflict areas)

Under uncongested traffic conditions vehicle right-of-way can be controlled by an intersection traffic signal. However, special treatment of vehicle priorities should be considered so as to model more realistic traffic behavior when queue spillback due to traffic congestion reaches or passes the upstream intersection. This research takes advantage of built-in VISSIM functionality (i.e., conflict areas) to define vehicle priorities at the signalized intersection. This can be applied at any position where two links overlap [96]. Thirty-two conflict areas have been implemented at individual signalized intersections with default parameter values.

I) Development of traffic incident environment

To examine the performance of the GATIS-V2V model under various traffic states a traffic incident is modeled in several of the experimental trials. VISSIM users have to devise novel methods to represent incident conditions, by incorporating underlying functions or manipulating relevant objects, as the traffic simulation model does not provide a direct means to realize a traffic incident. This research employs three methods to implement traffic incident conditions: speed zones, desired vehicle speed control, and traffic signals.

Method 1: speed zone

This is the most straightforward method to model a traffic incident. A speed zone is placed on the traffic incident link with a reduced speed (traffic incident speed). In VISSIM a speed zone reduces the vehicle speed from its current speed to the speed of the speed zone. One critical characteristic of speed zones is that vehicles do not begin to decelerate until they enter the speed zone. Thus, the speed zone should include the incident area and the upstream area required to decelerate to the incident speed.

Method 2: desired vehicle speed control

In this method script is written to continuously monitor vehicles at a specific location on one link (i.e., traffic incident link). When the simulation time reaches the incident beginning time the desired speed of vehicles passing the pre-determined segment on the traffic incident link is changed to the incident speed. When the incident is resolved or when vehicles leave the incident area, the vehicles are assigned their original speed. As this method of incident implementation requires the execution of scripts that monitor vehicle's located on the incident link, the method can significantly increase simulation run time.

Method 3: traffic signal head (used in this research)

Traffic signals can be installed at the beginning of the traffic incident area with red time activated for the traffic incident time duration. This method stops vehicles, which is somewhat different from a real traffic incident case where vehicles may slowly pass through the traffic incident area. To help account for this behavior this research releases one vehicle at the constant time interval (e.g., one vehicle every 90 seconds in this research) from the incident location for the effective incident time duration.

3.2.2 Initialization Data Process

The initialization data process produces historical link travel time database and origin-destination and route information for participating and non-participating vehicles. This data is utilized to initialize the GATIS-V2V model. Figure 7 illustrates the concise flow of necessary tasks and relationship between the initialization data process and main process. Briefly, a set of replicate runs of the network are utilized to develop a set of historical travel times. A single set of O-D data and route information for all vehicles to be simulated is then generated. Those vehicles that are identified as participating (i.e., instrumented vehicles) are assigned random origin-destination pairs. Only network boundary nodes are utilized as origins and destinations. They are then assigned routes based on optimizing (i.e., minimizing) travel time given the historical data base. Non-participating vehicles are also assigned random origin-destination pairs. However, the route between these O-D pairs is assigned randomly, given the path generation constraints previously discussed. The participating and non-participating vehicle routes are them utilized in the GATIS-V2V experiments. It is noted that a "no communication" experiment assumes that no vehicles receive or transmit information, and therefore no re-routing occurs during the simulation run. This may be considered the base, non-ATIS, performance. Additional detail for the initialization process is given in the following sections.

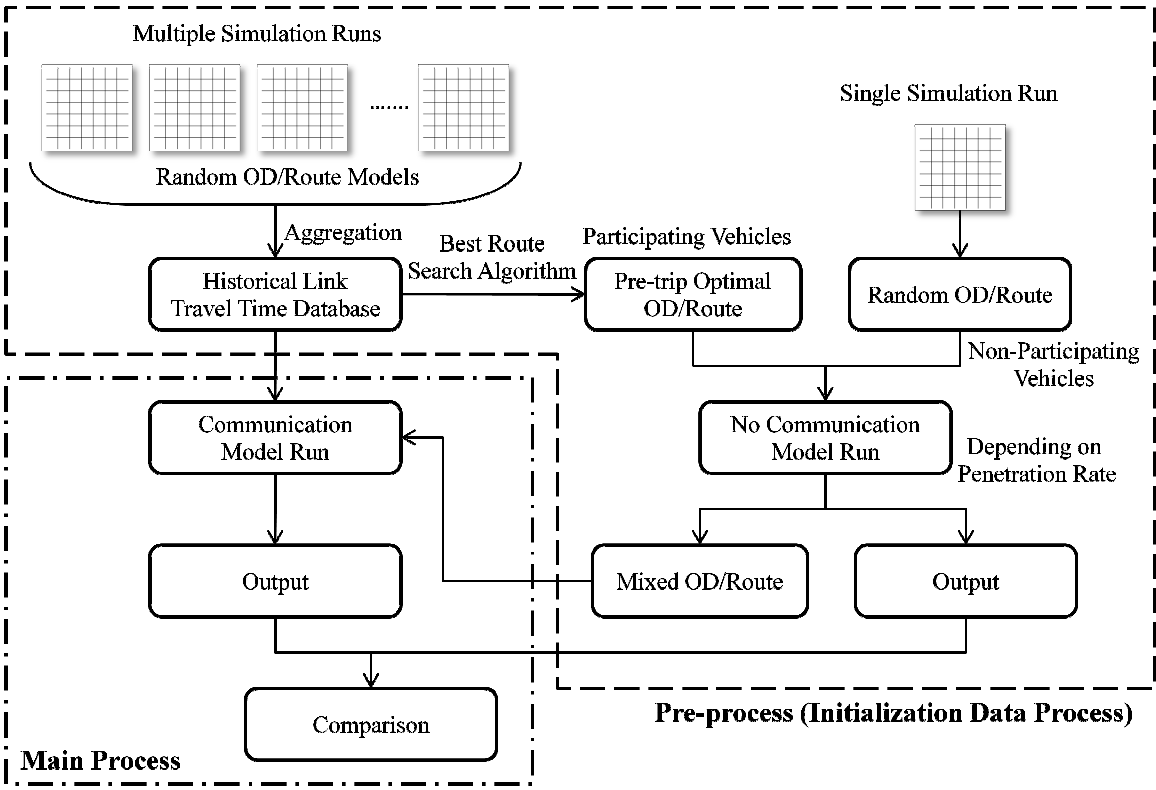


Figure 7: Pre-process (Initialization Data Process) of GATIS-V2V Model

A) Origin-Destination and Route generation

When a vehicle is generated at its entering node (i.e., origin), the turning movement at the downstream intersection is determined randomly according to pre-designed turning ratios (e.g., 15%, 70%, and 15% for the left, through, and right movements, respectively).

Vehicles are not allowed to select movements that would violate the previously discussed route constraints. The movement at each intersection continues to be randomly selected until the destination is reached. This method is used for the replicate runs utilized to construct the historical database and the single run utilized to determine the routes of the non-participating vehicles.

B) Historical link travel time archive

Even with the passing of data between instrumented vehicles often the on-board travel time database can not secure traffic state information of the entire traffic network. That is, some links may not have been traversed by an instrumented vehicle, link travel time data may be discarded due to age, or sufficient communication groups may not exist that a vehicle receives all available data. For these links to be included in potential routes it is necessary to impute estimated travel times for missing data. Accordingly, this research effort emulates historical link travel time archives through the use of replicate runs of random O-D/Route data. This historical database is used to fill in missing travel time data or supplement the travel time estimation where insufficient data exists in the STM. The historical travel database is determined according to the following.

$$Hist(j,k) = \frac{1}{M}\sum_{l=1}^{M}\frac{1}{N_{jk}^{l}}\sum_{i=1}^{N_{jk}^{l}}T_{ijk}^{l}$$

where:
M = total number of simulation runs
N_{jk}^{l} = number of travel times in the database on link *j*, for time bin *k*, and at *l*th simulation run
T_{ijk}^{l} = *i*th travel time in the database on link *j*, for time bin *k*, and at *l*th simulation run

C) Pre-trip optimal O-D/Route generation for participating vehicles

The GATIS-V2V model provides participating vehicles with the pre-trip optimal route information. These optimal routes are calculated using Dijkstra's algorithm (described in more details later) based on the archived historical link travel time and O-D information derived in Section 3.2.2 A). The derived optimal routes are chosen for the participating vehicles in the no communication model. These pre-trip optimal routes can be considered as the routes drivers take based on their long-term traffic condition experience. In some instances it will be seen that this route information may be updated prior to a vehicle initiating their trip according to non-recurrent traffic conditions, such as traffic incident, that such drivers may be made aware of through other means, such as radio or web sources.

D) Initial route determination and non -ATIS (no communication) model run

When vehicles are generated, each vehicle is randomly assigned as a participating or non-participating vehicle according to the desired participation rate (i.e., penetration ratio). Participating and non-participating vehicles are assigned pre-trip O-D/Route (Section 3.2.2 C)) and random O-D/Route (Section 3.2.2 A)) information, respectively. Figure 8 highlights the mixed O-D/Route generation process seen in Figure 7. These O-D/Routes are saved as the mixed O-D/Route information and used as O-D/Route information in the GATIS-V2V model run.

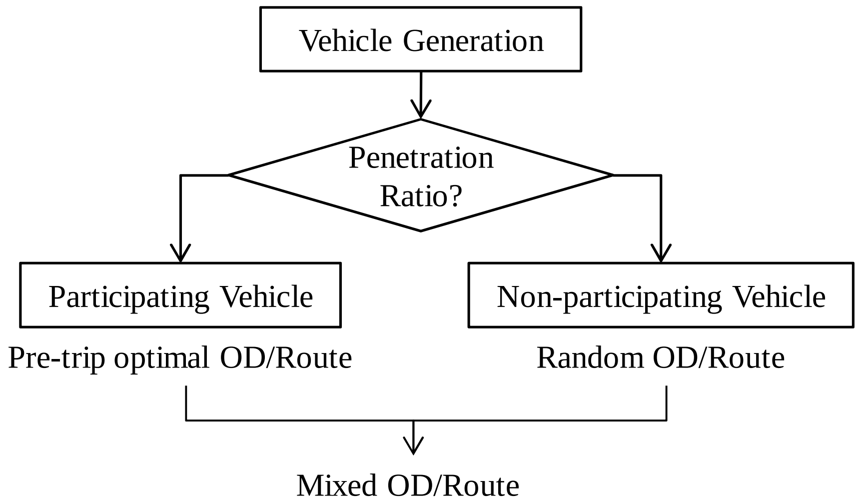


Figure 8: Mixed O-D/Route Generation Process

In the non-ATIS (i.e., no communication) model vehicles are not capable of implementing wireless vehicle communication and thus drivers are assumed to travel along their original path to the destination. Therefore, the GATIS-V2V model can be evaluated by comparing with the no communication model.

3.2.3 Summary

This research designed various operational pre-processes required to implement the GATIS-V2V model. This stage includes defining the vehicle turning movement condition, designating turning movement-dependent link travel times, defining the on-board database structure and data packet size, designing an unique methodology for vehicle turning in the GTIS-V2V model, implementing vehicle priorities, identifying methods for modeling traffic incidents, and overcoming the system resource limitation with the dynamic update algorithm of participating vehicles and simulation time.

Besides the operational processes, various basic data should be prepared before the actual communication model is run. For example, in order to fill and impute the un-recorded data cell in the STM historical travel time database should be archived and pre-trip optimal O-D/Route information need to be calculated from this historical database for participating vehicles and random O-D/Route information from single random simulation run for non-participating vehicles. For evaluating the scenario-dependent system performance associated O-D/Route information are arranged and simulation output of no communication model based on the produced O-D/Route should be secured in this stage for comparison of communication model output.

3.3 Main Process

3.3.1 GATIS-V2V Communication Model

The GATIS-V2V communication model is run using the scenario-dependant mixed O-D/Route information for all generated vehicles. Responding to information received through communications participating vehicles may be re-routed to less congested paths identified from the prevailing traffic state information. The performance of the GATIS-V2V model is measured with respect to various performance metrics described below.

3.3.2 GATIS-V2V Performance Metrics

After completing all required pre-processes, this research investigates the performance of the GATIS-V2V model. This investigation process is considered in two stages; first the three system modules (i.e., vehicle communication, database management strategy, and dynamic route guidance modules) are verified and second the GATIS-V2V response is evaluated with respect to the three underlying system parameters.

A) Performance metrics for system verification

It is mandatory to verify the operation of the three key modules executed in the GATIS-V2V model prior to the comprehensive system evaluation. The verification process is accomplished by considering the reasonableness of model outputs and comparing outputs with preceding research.

- Vehicle communication

Average number of communication groups and number of participating vehicles in a communication group.

- Data speed

Average elapsed time required for traffic data to reach a pre-determined area.

- Data coverage area

Average number of links with updated travel time data on individual participating vehicles.

- On-board travel time management strategy

Number of re-routing participating vehicles.

- Dynamic route guidance system

Reliability and accuracy test - travel time difference between the system predicted and actual on traveled routes.

B) Performance metrics for model evaluation

The main performance metrics utilized are the average travel time savings of participating and non-participating vehicles, and re-routing vehicles, followed by the temporal and spatial analysis of vehicle re-routing and travel time savings patterns of participating vehicles.

3.4 System Development

Figure 9 and Figure 10 depict the processes that participating and non-participating vehicles go through in the GATIS-V2V model, from a vehicle's generation to its network departure. The GATIS-V2V model generates constant vehicle headways at the entering links according to the desired hourly traffic flow rate. Upon generation participating and non-participating vehicles are assigned their O-D/Route information from the pre-defined database (i.e., mixed O-D/Route) discussed previously. Route information of participating vehicles can be updated in their own on-board computer instantly or every system update time interval via a dynamic route guidance module. The GATIS-V2V model monitors vehicle location on an XY coordinate system until it departs the network, helping to identify the time a vehicle passes link and whether the spatial communication condition with adjacent vehicles is satisfied for traffic data sharing.

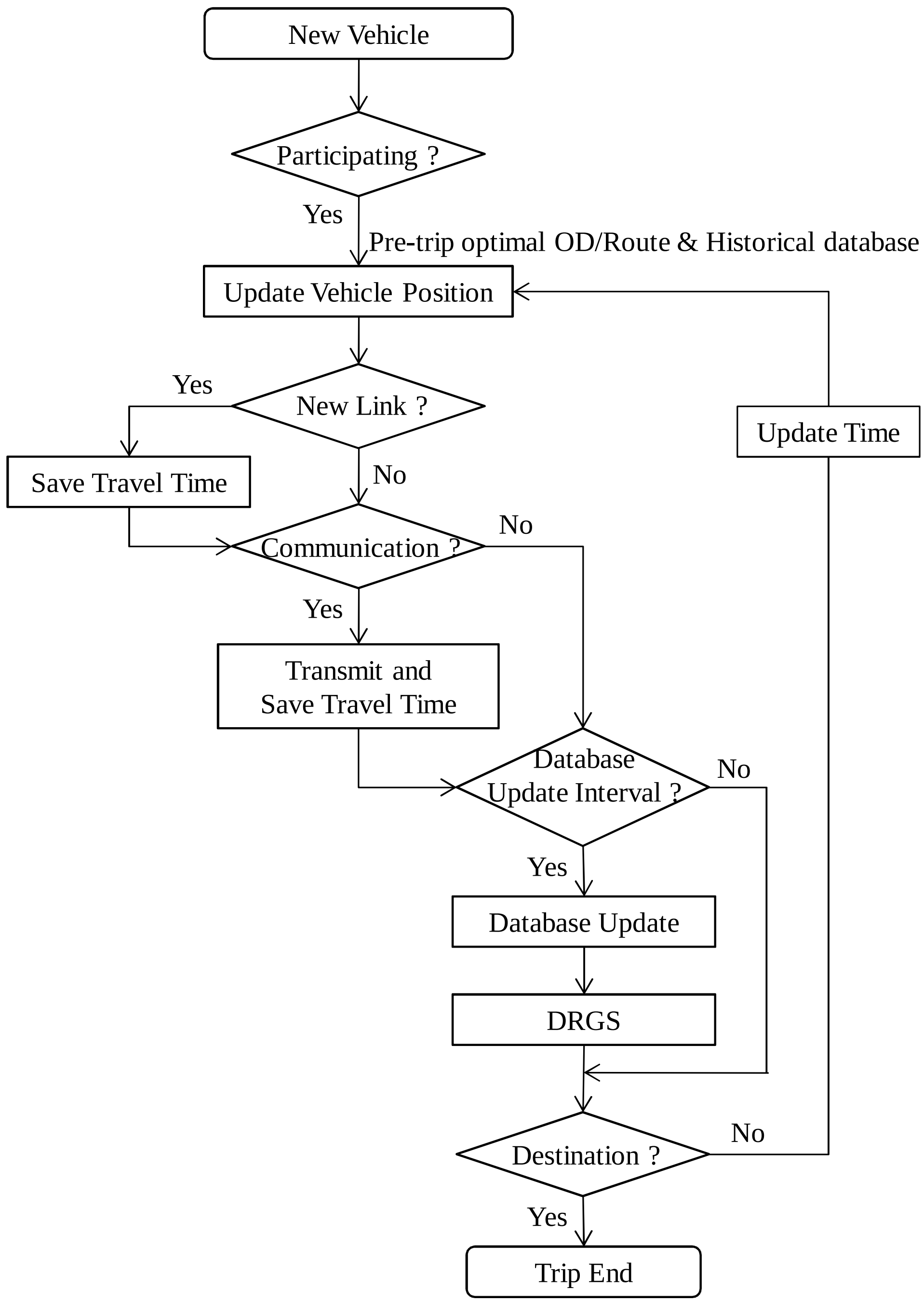


Figure 9: System Flow Chart for Participating Vehicles

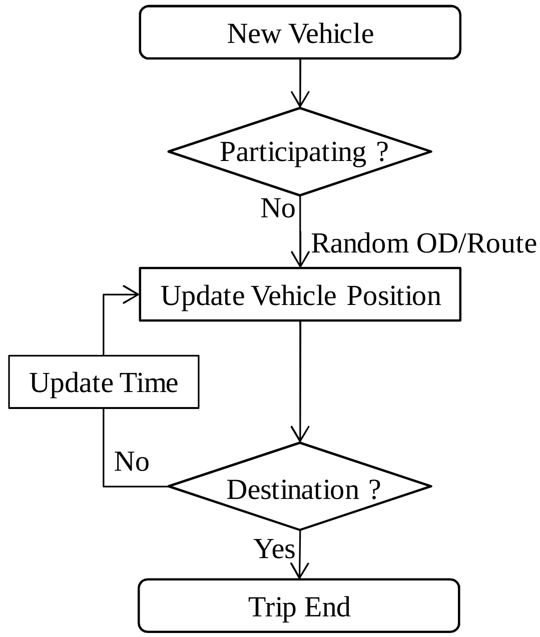


Figure 10: System Flow Chart for Non-participating Vehicles

3.4.1 Microscopic Traffic Simulation Model (VISSIM and VISSIM COM)

As stated previously, this research employs an existing commercial microscopic simulation model (i.e., VISSIM), because it can model individual vehicles based on already established and broadly accepted driver models such as car following and lane change models [85]. VISSIM, a German acronym for "Verkehr In Staedten SIMulation (traffic in towns – simulation)", is a microscopic, stochastic, time step and behavior based simulation model developed at the University of Karlsruhe, Germany, in the early 1970s and distributed by Planung Transport Verkehr (PTV) Transworld AG and Innovative Transportation Concepts [97] in North America.

VISSIM includes a VISSIM Component Object Model (COM) interface through which users can access and control objects in the traffic network at runtime. This interface makes it feasible for users to elicit data from vehicles, save output periodically, change the vehicle movement rules, and even apply dynamic vehicle control methods [98, 99]. Consequently, VISSIM is an appropriate tool to simulate the ATIS using V2V communication.

3.4.2 Communication Model

As mentioned in Chapter 2, researchers in the wireless communication research field (e.g., MANET and VANET) have developed and tested numerous communication protocols and algorithms under various conditions. Since the current effort focuses on ITS application development impacts on vehicle travel times, an ideal communication environment is initially assumed, such as no signal interference and no data loss during communication. Also, the reactive routing protocol is employed because the routing time is less important than the available communication bandwidth in the GATIS-V2V model possibly dealing with data transmission of huge database. Therefore, all data saved in individual participating vehicles are shared with all neighboring vehicles while communication connections are established. Future efforts will endeavor to investigate the impact of non-ideal communication on the proposed ATIS.

A) Communication group formation

Prior to actual data sharing between vehicles, the GATIS-V2V model forms communication groups composed of individual participating vehicles for the multi-hop data communication. These groups are formed every communication time interval (i.e., 1 second in this research). To form these groups the following method is used. Initially, one participating vehicle is assigned to the first communication group. This vehicle searches for surrounding vehicles within its communication radio range. Vehicles within radio range are added to the communication group. Next, the added vehicles search for vehicles within their communication range. This process is repeated until no additional vehicles may be included in the communication group. Next a participating vehicle not assigned to a communication group is selected. The group creation process is then repeated. This continues until all vehicles have been assigned to a group. It is noted that it possible for a communication group to contain a single vehicle, implying that the vehicle is out of communication radio range of any other participating vehicles. As traffic flow, penetration ratio, and communication radio range increase, more data sharing is facilitated.

The algorithm to determine communication groups is as follows:

$For\ i = 1\ to\ APV$

$\quad If\ v(i) \neq 0\ then$

$\quad\quad G_n^0 \ni v(i)\ and\ v(i) = 0$

$\quad\quad For\ j = 1\ to\ APV$

$\quad\quad\quad If\ v(j) \neq 0\ and\ AG_n^0 \neq v(j)\ and\ Dist\left(AG_n^0,\ v(j)\right) \leq RR\ then$

$\quad\quad\quad\quad G_n^1 \ni v(j)\ and\ v(j) = 0$

$\quad\quad\quad End\ If$

$\quad\quad Next$

$\quad\quad For\ x = 1\ to\ \infty$

$\quad\quad\quad If\ g_n^x > g_n^{x-1}\ then$

$\quad\quad\quad\quad r = x + 1$

$\quad\quad\quad\quad For\ k = 1\ to\ APV$

$If\ v(k) \neq 0\ and\ AG_n^x \neq v(k)$

$and\ Dist(AG_n^x, v(k)) \leq RR\ then$

$G_n^r \ni v(k)\ and\ v(k) = 0$

$End\ If$

$Next$

$ElseIf\ g_n^x = g_n^{x-1}\ then$

$n = n + 1\ and\ r = 0$

$Exit\ For$

$End\ If$

$Next$

$End\ If$

$Next$

where:
APV = all participating vehicles
$v(\#)$ = #th vehicle in the participating vehicle array $v(\ )$
G_n^r = participating vehicle array in nth communication group and rth routing round
AG_n^r = individual participating vehicles in G_n^r
$Dist(\#, \#\#)$ = Euclidean distance between vehicles # and ##
RR = communication radio range
g_n^r = number of participating vehicles in communication group n up to rth routing round
n = communication group number
r = communication routing round number

B) Data dissemination process

After communication groups are constructed stored travel times are disseminated between participating vehicles in the communication group. To efficiently emulate the data sharing the first vehicle in each communication group gathers all travel time information from the other vehicles in the communication group into its STM. As part of this aggregation it is assured that the travel time data from individual vehicles is considered only once through a data screening process that incorporates a vehicle ID associated with each travel time data point. Then, the STM of all participating vehicles, except the first vehicle in the communication group, are deleted and the transmitted and saved travel time information in the first vehicle is transferred to other vehicles in the communication group. This algorithm guaranties that all participating vehicles in a communication group have the same contents in their STM at the end of a time interval.

The algorithm is as follows:

$For\ i = 1\ to\ ACG$

$\quad For\ j = 2\ to\ AV^i$

$\qquad If\ VID^{CG(i,1)} \neq VID^{CG(i,j)}$

$\qquad\quad T^{CG(i,1)} \ni T^{CG(i,j)}\ and\ VID^{CG(i,1)} \ni VID^{CG(i,j)}$

$\qquad End\ If$

$\qquad T^{CG(i,j)} = 0\ and\ VID^{CG(i,j)} = 0$

$\quad Next\ j$

$\quad For\ j = 2\ to\ AV^i$

$\qquad T^{CG(i,j)} \ni T^{CG(i,1)}\ and\ VID^{CG(i,j)} \ni VID^{CG(i,1)}$

$\quad Next\ j$

$Next\ m$

where:
ACG = all communication groups
AV^i = individual vehicles in communication group i
$CG(i,\ j)$ = jth vehicle in communication group i
$VID^{CG(i,j)}$ = individual vehicle IDs saved in $CG(i,\ j)$ for all links and time bins
$T^{CG(i,j)}$ = individual travel times saved in $CG(i,\ j)$ for all links and time bins

3.4.3 On-board Travel Time Database Management Strategy

DRGS aims to determine the most cost-effective route from the origin to the destination. The cost may be the link distance, travel time, or other potential measures. For this effort travel time is utilized as the input data into the operating DRGS. Therefore, efficient management of the spatial and temporal travel time information is a key issue that should be taken into consideration for the successful implementation of the GATIS-V2V model.

System update time interval is set with system elapsed time in this research. If the update time interval is too short the system is computationally expensive (extremely long simulation time) and resulting route information may not be reliable due to sparse data. On the other hand, a significantly long time interval may fail to detect the non-recurrent traffic state in the timely manner. Therefore, the update time interval is a critical system component, influencing system reliability and efficiency.

An on-board database update process is executed every system update time interval, or instantly when traffic congestion messages are received. Currently, the GATIS-V2V model estimates travel time for a link using a simple average method on that link for the given time interval. After estimating link travel times, the GATIS-V2V model predicts the short-term travel time based on the temporal relationship between estimated travel time for current time interval and several past time intervals. Again, a simple average of the time interval data is utilized.

The algorithm is as follows:

$For\ p = 1\ to\ APV$

$\quad For\ j = 1\ to\ AL$

$\quad\quad For\ t = CT - PT\ to\ CT$

$\quad\quad\quad If\ C_{j,t}^{p} \geq 0\ then$

$$DB(p,\ j,\ t,\ 0) = \frac{\sum_{m=1}^{C_{j,t}^{p}} DB(p,j,t,m)}{C_{j,t}^{p}}$$ Estimation

$Endif$

$Next$

$$DB(p,\ j,\ CT+1,\ 0) = \frac{\sum_{n=1}^{PT+1} DB(p,j,n,0)}{PT+1}$$ Prediction

$Next$

$Next$

where:
AL = all links in STM
CT = bin number for the current simulation time
PT = number of past time bins used for travel time prediction
$C_{j,t}^{P}$ = number of travel time records for link j and time bin t of vehicle p
$DB(p,\ j,\ t,\ 0)$ = estimated link travel time for link j and time bin t of vehicle p

3.4.4 Dynamic Route Guidance System (DRGS)

Various algorithms to find the most cost-effective route have been introduced in the literature, such as Bellman-Ford, Floyd-Warshall and Dijkstra's algorithms [53]. Among them, this research employs Dijkstra's algorithm, the most efficient method available for computing shortest paths from one node (origin) to all others (destination) in directed graphs (digraphs) having all link costs nonnegative [53]. For this implementation a directed graph design is utilized to solve Dijkstra's algorithm.

A) Directed graph (Digraph) design

As stated earlier, the travel time database discerns the travel time of one roadway segment according to the turning activities conducted at the upstream and downstream intersections. To account for this in the implementation of Dijkstra's algorithm each intersection is converted into three notional nodes in the digraph, except origin and destination nodes associated with boundary links, as can be seen in Figure 11. Each node is given unique node number. Figure 12 is the example of a digraph with 6X6 urban grid traffic network, focusing on eastbound and northbound, obeying the previously discussed conditional turning movement rules. For ease to implement DRGS in the GATIS-V2V model 8 digraphs for the 6X6 urban grid traffic network are designed, depending on the origin and destination locations.

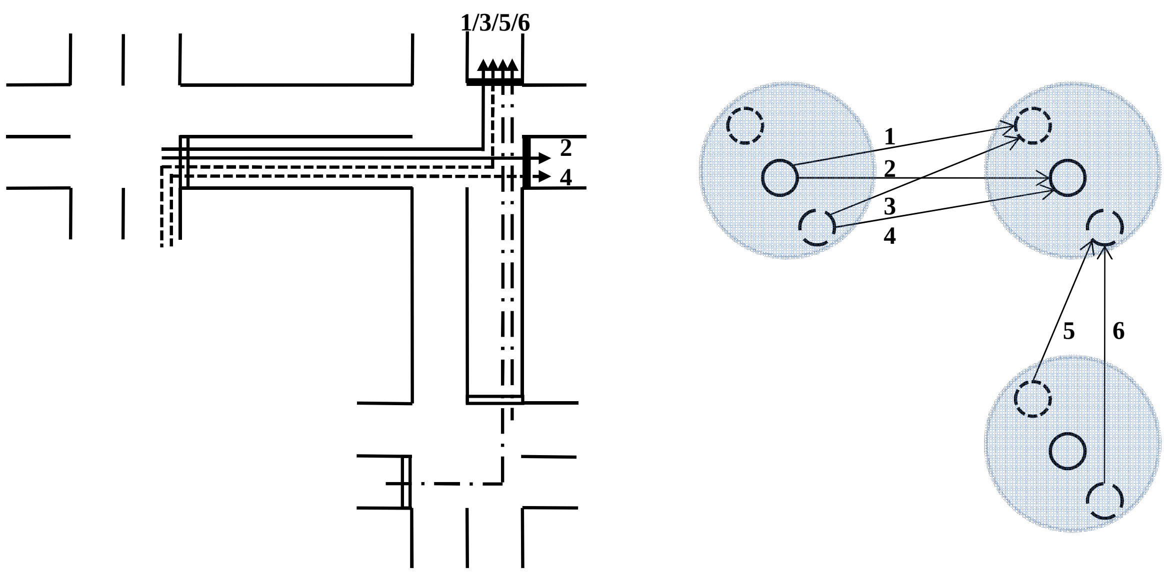


Figure 11: Matching Process between Actual Links and Digraph Links

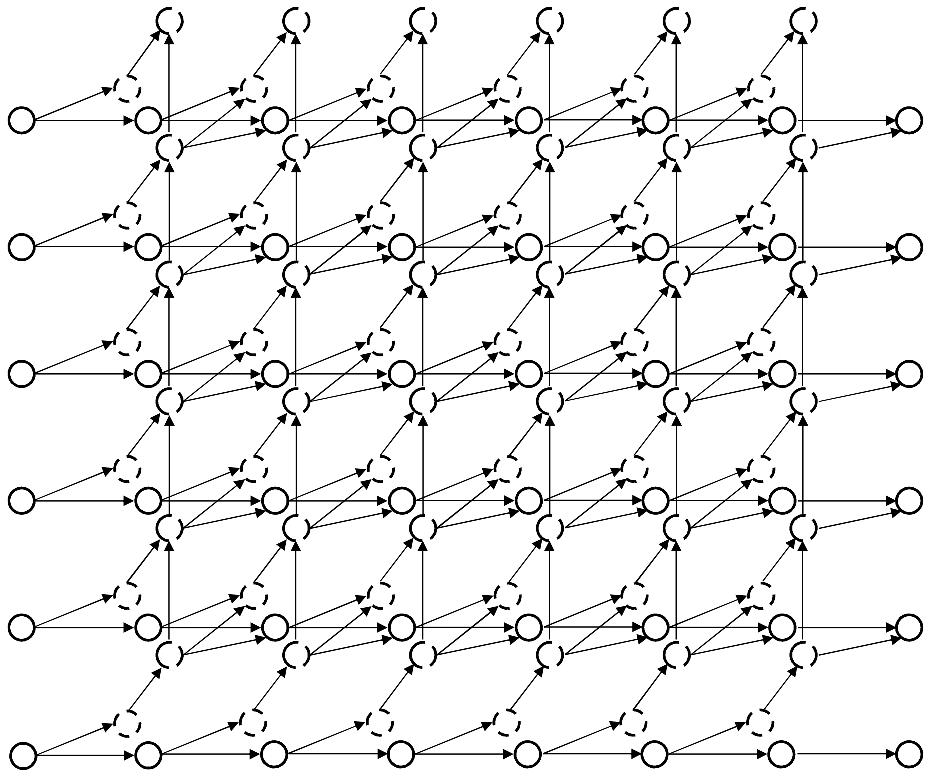


Figure 12: Digraph of Eastbound and Northbound Routes

Note: Eastbound through, Northbound through, Eastbound left

B) <u>Dijkstra's algorithm</u>

GATIS-V2V model employs Dijkstra's algorithm to find the most time-efficient route every system update time interval or instantly as needed, followed by supplementary processes. The main terminologies are borrowed from Reference [53].

The algorithm is as follows:

Step 1: Initialization

Initialize travel time with s (current node = origin node)

$$\begin{Bmatrix} v[temp] = 0 & , if\ temp = s \\ v[temp] = +\infty & , otherwise \end{Bmatrix}$$

Mark all nodes temporary and $per = s$ as next permanent node

Step 2: Processing

Mark node per permanent and update travel time for every link leading from per to $temp$

$v[temp] = min\{v[temp], v[per] + TT_{per,temp}\}$

$d[temp] = per \quad , if\ v[temp]\ changed$

Step 3: Next permanent node and stopping rule

$\mathrm{v}[per] = \min\{v[temp]\}$

$$\begin{Bmatrix} v[per] = shortes\ travel\ time\ \rightarrow Step\ 4 & , if\ per = d\ and\ no\ more\ temp\ to\ per \\ per = next\ permanent\ node\ \rightarrow Step\ 2 & , otherwise \end{Bmatrix}$$

Step 4: Travel link list and vehicle type list update

After finding the shortest route composed of sequential notional nodes in the digraph, they are interpreted into actual link information and vehicle type list is updated based on the relation between updated consecutive links.

where:
s = origin node (current node)
per = permanent node
d = destination node
$temp$ = temporary nodes
$v[k]$ = travel time of shortest path from s to node k
$d[k]$ = node preceding k in the best known route from s to k
$TT_{i,j}$ = travel time between node i and j

3.4.5 Summary

The basic system requirement for GATIS-V2V includes three key modules: vehicle communication model, on-board database management strategy, and dynamic route guidance system. Vehicle communication can consist of two fundamental processes; one is the communication group formation like communication node routing algorithm and the other is the actual traffic data transmission within an established communication group. In addition, the efficient management of the traffic database resided in each participating vehicle and accurate estimation and prediction of the traffic state in a timely manner is a core element to generate more reliable route information. Finally, individual participating vehicles autonomously search for the optimal route from the current location to the final destination based on the estimated and predicted traffic information. This GATIS-V2V model composed of three key modules are evaluated and compared with other various models.

3.5 System Performance-enhancing Functions

The GATIS-V2V model developed (i.e., the basic GATIS-V2V model) so far may not achieve the intended benefits due to untimely detection of and response to non-recurrent traffic states, unreliable estimated and predicted travel time, and failure to account for driver characteristics. This behavior will be seen in the experimental results discussed in the subsequent chapters. Accordingly, the GATIS-V2V model is enhanced with three complementary functions (i.e., autonomous automatic incident detection algorithm, minimum travel time sample size rule, and drivers' route selection rule) to improve the system efficiency and reliability (i.e., the advanced GATIS-V2V model).

3.5.1 Autonomous Automatic Incident Detection (AAID) Algorithm

In the basic GATIS-V2V model vehicles provide link travel time data when the vehicle exits a link. Thus, a vehicle will not collect and communicate traffic incident-related travel times until the vehicle passes over the incident link and enters a new link. Thus, other participating vehicles will remain unaware of a degraded downstream traffic state until a downstream vehicle successfully passes the incident and communicates the updated travel time data. To address this weakness an AAID algorithm detects local non-recurrent traffic states by measuring the time difference between a vehicle's elapsed time on the given link and the link entering time. If the time difference is sufficiently greater than the pre-defined time criterion (e.g., historical link travel time) the vehicle will issue and disseminate a traffic congestion message to neighboring vehicles. This is different from the incident detection system developed and tested in Texas Transportation Institute (TTI) in 1996 in that they employed cellular phones and the traffic operation center investigated unusual traffic patterns observed in the field [100]. Vehicles informed of the downstream congestion instantly update their database and route to avoid the incident area. Currently the congestion message sets the travel time as "unattainable", or essentially infinite, forcing an upstream participating vehicle to re-route, if possible. The actual travel time of the traffic incident link is updated when vehicles enters the next link. Figure 13 illustrates the concept of AAID on one link, followed by the algorithm.

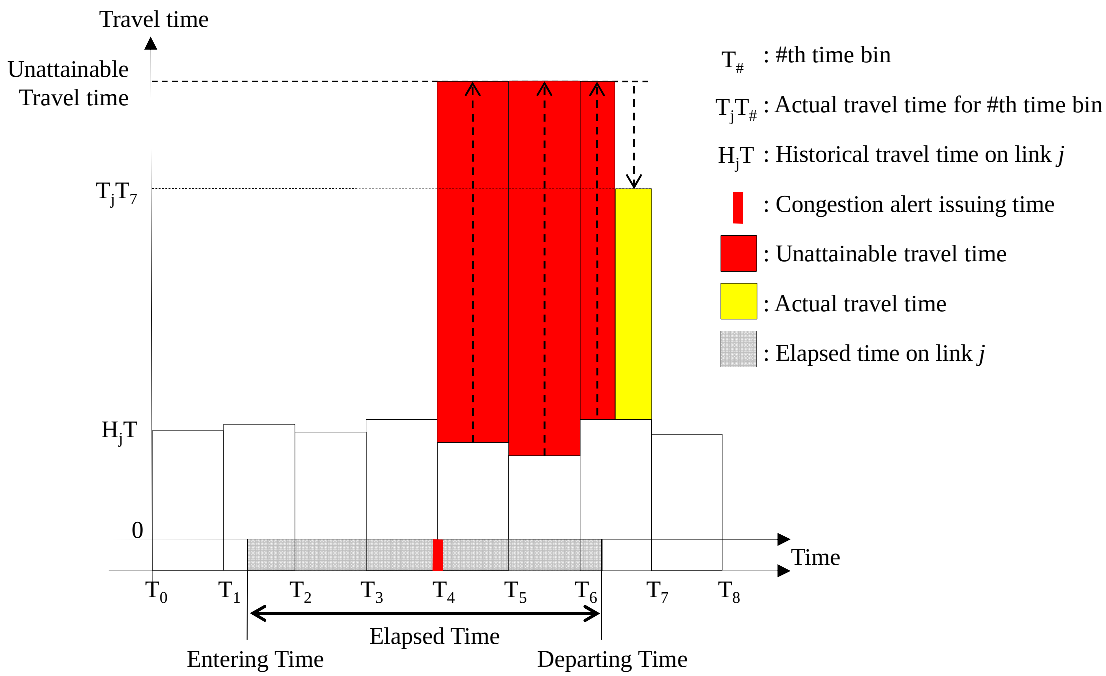


Figure 13: Concept of Autonomous Automatic Incident Detection (AAID) Algorithm

The algorithm is as follows:

$$If\ ST_j^i - ET_j^i \geq K * Hist(j)\ then$$

$$LT_{j,t}^i = UT$$

$$Elseif\ \ ET_{j+1}^i > 0\ then$$

$$LT_{j,t}^i = ET_{j+1}^i - ET_j^i$$

$$Endif$$

where:
$Hist(j)$ = historical link travel time for link *j*
ET_j^i = link *j* entering time of participating vehicle *i*
ST_j^i = staying time of participating vehicle *i* on link *j* (current time)
K = user-defined congestion parameter
UT = unattainable link travel time
$LT_{j,t}^i$ = actual travel time of vehicle *i* on link *j* and time *t*

3.5.2 Minimum Travel Time Sample Size Rule

Traffic information systems collecting real time traffic data from probe vehicles rather than fixed-location surveillance equipments should secure a sufficient number of probe vehicle data to reliably estimate travel time. Unlike the centralized and fixed infrastructure traffic information system, the basic GATIS-V2V model is likely to have relatively fewer travel time records as communication links between vehicles can be easily established and broken, and sufficient participating vehicles may not exist to adequately sample all links. While the basic GATIS-V2V model estimates travel time with any sample size, the advanced GATIS-V2V model utilizes a minimum sample size to estimate an updated travel time. Where the minimum sample size is not met, the historical link travel time is utilized in calculating the updated estimated route travel times.

A) Determination of minimum sample size

The advanced GATIS-V2V model calculates the minimum sample size for individual links based on the archived historical travel time. At first, the normality test is conducted on the historical travel time for individual links with Shapiro-Wilk test. If null hypothesis that these data are from a normal distribution is not rejected, the minimum samples size is calculated with Equation 1. Otherwise, the minimum sample size is calculated using the heuristic method below. The method sets a 0.01% sampling ratio (TP) to randomly select travel times TN_j times from historical travel time data of link j, over the entire simulation time period and from the multiple replicate simulation runs. This process is repeated M times and if Root Mean Square Error (RMSE) between average travel time (SA_j^m) for each sampling process (m) and total average travel time (AM_j) of link j is smaller than user-defined allowable error ratio (ε) and TN_j is not over the maximum sample size for one system update time interval (B_j), TN_j is the minimum sample size and average of SA_j^m (SA_j) is reliable travel time of link j. Otherwise, TP increases by 0.01% and above processes are repeated until it satisfies the stopping rule or the upper boundary sample size (B_j) is accepted as the minimum sample size for link j.

$For\ j = 1\ to\ AL$

$$MS_j = \left(\frac{t_j \times SD_j}{\varepsilon}\right)^2 \qquad \text{Equation 1}$$

$Next$

where:
MS_j = minimum sample size for link j
t_j = t-table value
SD_j = sample standard deviation for link j
ε = user-specified allowable error

The algorithm is as follows:

$For\ j = 1\ to\ AL$

$TN_j = TR_j \times TP$

$While$

$For\ m = 1\ to\ M$

$For\ n = 1\ to\ TN_j$

$RTT_j^{m,n}$

$Next$

$$SA_j^m = \sum_{n=1}^{TN_j} RTT_j^{m,n} / TN_j$$

$Next$

$$RMSE_j = \sqrt{\frac{\sum_{m=1}^{M}(SA_j^m - AM_j)^2}{M}}$$

$If\ RMSE_j \leq AM_j \times \varepsilon\ then$

$If\ TN_j \leq B_j\ then$

$MS_j = TN_j$

$$SA_j = \sum_{m=1}^{M} SA_j^m \Big/ M$$

$Else$

$MS_j = B_j$

$SA_j = AM_j$

$EndIf$

$TP = 0.0001$

$Exit\ While$

$Else$

$TP = TP + 0.0001$

$TN_j = TR_j \times TP$

$EndIf$

$End\ While$

$Next\ j$

where:
TN_j = number of randomly selected travel time records for link j
TR_j = number of all travel time records for link j
B_j = maximum number of travel time records for link j for one system update time interval (i.e., upper boundary of the minimum sample size)
TP = percentage to determine TN_j from TR_j (default = 0.0001)
M = maximum number of sampling process (default = 20)
$RTT_j^{m,n}$ = nth randomly selected travel time in the mth sampling process for link j
SA_j = reliable sample average travel time for link j

SA_j^m = sample average travel time for link j in the mth sampling process
AM_j = average travel time of all travel time records for link j
$RMSE_j$ = root mean square error of sample average travel time for link j

From this heuristic method the biggest minimum sample size for 300vph and 514vph is 17 and 29, respectively. Thus, the minimum sample size for each system update time interval and each link is set to 30 in the STM.

B) Advanced on-board travel time database management strategy

The advanced GATIS-V2V model compares the number of travel time records with the minimum sample size for the link. When participating vehicles store sufficient travel time records, the estimated travel time can be considered as a reliable travel time; otherwise, it the historical link travel time is utilized.

The algorithm is as follows:

$For\ p = 1\ to\ APV$

$For\ j = 1\ to\ AL$

$For\ t = CT - PT\ to\ CT$

$If\ C_{j,t}^p\ \geq MS_j\ then$

$$DB(p,\ j,\ t,\ 0) = \frac{\sum_{m=1}^{C_{j,t}^p} DB(p,j,t,m)}{C_{j,t}^p} \qquad \text{Estimation}$$

$Else$

$$DB(p,\ j,\ t,\ 0) = Hist(j)$$

$Endif$

$Next$

$$DB(p,\ j,\ CT+1,\ 0) = \frac{\sum_{n=1}^{PT+1} DB(p,j,n,0)}{PT+1} \qquad \text{Prediction}$$

$Next$

$Next$

3.5.3 Drivers' Route Choice Rule

Small differences in the travel time between the current and the system-guided routes can result in unnecessary routing. This research takes advantage of Mahmassani's boundedly rational switching rule [81] in the drivers' route choice model (Equation 2). Mahmassani stated that an indifference band of 0.2 provides reasonable overall behavior and the largest system-wide improvement in travel time [79, 101]. However, the experiment output is limited to the particular network configuration used and to the particular information strategies [79], thus this research performs a sensitivity analysis (Chapter 6) of indifference band with system-dependent underlying parameters.

$$\delta_i(n) = \begin{cases} 1, & if\ TTC_i(n) - TTB_i(n) > max\ [\eta_i(n) * TTC_i(n), \tau_i(n)] \\ 0, & otherwise \end{cases} \qquad \text{Equation 2}$$

where:
$\delta_i(n)$ = binary indicator equal to 1 if participating vehicle i switches to the system-guided route from node n to the destination, 0 otherwise.
$TTC_i(n)$ = travel time on the current route from node n to the destination
$TTB_i(n)$ = travel time on the system-guided route from node n to the destination
$\eta_i(n)$ = relative indifference band for participating vehicle i
$\tau_i(n)$ = minimum improvement in the remaining travel time from node n to the destination, necessary for participating vehicle i to switch to the system-guided route, with $\tau_i(n) \geq 0$

3.5.4 Summary

A variety of technologies and methods have been proposed and implemented to improve the ITS applications in the real-world or research field. This study proposes three complimentary functions to improve the efficiency of the basic GATIS-V2V model such as autonomous automation incident detection (AAID) algorithm, minimum sample size rule, and drivers' route choice rule. AAID is intended to detect the traffic incident to more quickly respond and broadcast to the public to minimize its effect, minimum sample size rule attempts to increase the reliability of the estimated travel time, and drivers' route choice rule is applied to reflect more realistic route choice pattern. The GATIS-V2V model utilizing these functions also will be evaluated under various system parameter-dependent scenarios.

3.6 Summary

This chapter discusses several processes to develop and run the GATIS-V2V model: pre-process (operational and initialization data processes) and main process (model development and introduction of complementary functions). Operational pre-process establishes the basic rules for vehicle path selection, defines the on-board database structure, creates efficient computing resource management methods, and set methods for implementation a traffic incident. The initialization data process archives the historical travel time database for data imputation as well as pre-trip and random O-D/Route data for participating and non-participating vehicles, respectively. The GATIS-V2V model is developed on the basis of the rules and definitions established in the operational pre-process and initiated with the historical database and O-D/Route information obtained from the initialization data process.

The GATIS-V2V model consists of three core modules: vehicle communication model, on-board database management strategy, and dynamic route guidance system. Three more supplementary functions (i.e., autonomous automation incident detection algorithm, minimum sample size rule, and drivers' route choice rule) are expected to enhance the performance of the GATIS-V2V model. The following chapters are devoted to investigation of the effect of three key system parameters (i.e., traffic flow, communication radio range, and penetration ratio) and three complementary functions on the system performance.

CHAPTER 4 EVALUATION OF GATIS-V2V MODEL IN NON-SIGNALIZED SIMPLE NETWORK

4.1 Introduction

This chapter investigates the basic characteristics of the GATIS-V2V model with three varying system parameters (i.e., traffic flow, communication radio range, and penetration ratio), introduces a centralized traveler information system using roadside equipment (RSE) for data communication between the TMC and participating vehicles [114], named the GATIS-V2R model, and compares their performance in terms of the average travel time savings of the participating and non-participating vehicles in a non-signalized simple traffic network under the traffic incident condition. GATIS-V2V is implemented as discussed in the previous chapter however the three system performance-enhancing functions are not implemented in this chapter. For the GATIS-V2R model two difference database update methods are studied GATIS-V2R-1 and GATIS-V2R-2.

4.2 System Development and Operation Methodology

4.2.1 Communication

Separate communication architectures are utilized for the GATIS-V2V and GATIS-V2R models. Future efforts will improve the vehicle communication module by incorporating more realistic communication-related parameter values configured for a specific region.

A) <u>The GATIS-V2R model</u>

The GATIS-V2R model exploits wireless communication between RSE and participating vehicles [102]. It is assumed that the entire traffic network is within the communication range of RSEs and the TMC. Traffic data is sent from participating vehicles to the TIC on a periodic basis to update the central database and route calculations algorithm. The length of the update interval is a user specified parameter. Here, a one second update interval is utilized.

B) <u>The GATIS-V2V model</u>

As discussed in the previous chapter at any update interval a communication link is dynamically established when participating vehicles are located within communication radio range. The GATIS-V2V model forms communication groups and instantaneous data exchange is possible through multi-hop communication within these groups. The data propagation scheme used is broadcasting with flooding, where data communication is conducted within the formed communication group without direct consideration of communication routing issues, no signal interference, and no data loss during communication [13, 103, 104].

4.2.2 Travel Time Database Update

As a participating vehicle traverses the network it saves its travel time to its local STM and communicates with roadside units or neighboring participating vehicles each update interval. The GATIS-V2R and GATIS-V2V update their travel time database, allowing for the calculation of revised routing information.

A) Database Update – the GATIS-V2R-1 (Centralized Instantaneous ATIS)

The GATIS-V2R-1 model is depicted on the left side in Figure 14. In the database representation shown in Figure 14 each column represents a link and the letters represent the link travel time for the current update interval. At the start of the GATIS-V2R-1 model run the STM is seeded with historical travel times (Step 1). Each time interval the GATIS-V2R-1 model central database receives traffic state information from participating vehicles that completed the traversal of a link since the previous update. For instance, in Step 2 of the GATIS-V2R-1 model update: two vehicles complete a traversal of link 1 in the latest update interval, one of link 2, one of link 3, none of link 4, and so on. The model aggregates the new link data and updates the link travel time in the database (Steps 3). Links where no new travel time data is obtained continue to use the previous (i.e., last recorded) travel time (Step 3 and Step 6).

B) Database Update – the GATIS-V2R-2 (Centralized Predictive ATIS)

Unlike the GATIS-V2R-1 model, the predictive update method provides some smoothing of the travel time data using a moving average approach. A depiction of the GATIS-

V2R-2 model is seen on the right side of Figure 14. In this implementation time is divided into bins, starting at time zero and continuing throughout the experiment. At any time *t* in the simulation run an estimated link travel time is the average of the travel time aggregated over the current time bin and the three previous bins. For this effort three minute bins are utilized. As seen in Figure 14 when the GATIS-V2R-2 model is initialized, the centralized travel time database is seeded with historical link travel times (Step 1). In Steps 2 and 3 estimated link travel times at any time *t* are computed as follows:

$$LTT_j = \sum_{T(\#)=T(C-3)}^{T(C)} \sum_{i=1}^{n_j^{T(\#)}} \frac{VTT_{j,T(\#)}^{i}}{n_j^{T(\#)}}$$

where:
LTT_j = Estimated travel time for link *j* at time *t*.
T(#) = Travel time bin number *#*, where bins are numbered consecutively from the start of simulation. *C* represents the bin number for the current simulation time.
$VTT_{j,T(\#)}^{i}$ = Travel time for Vehicle *i* to traverse link *j* during time bin *T(#)*.
$n_j^{T(\#)}$= The number of participating vehicles that complete their traversal of link *j* during time bin *T(#)*.

For example, cell (L1, T1) is the average of travel times for vehicles that complete their traversal of link L1 during time period T1 (i.e., from 0 seconds to 180 seconds), cell (L1, T2) is the average of travel times for vehicles that complete their traversal of link L1 during time period T2 (i.e., 181 seconds to 360 seconds), and so on. The L1 estimated travel time at time *t* = 700 is then the average of cells (L1, T1), (L2, T2), (L3, T3) and (L4, T4). Where no vehicles complete a traversal of a link during a time bin the bin travel time for that link is taken as the historical travel time (Step 6). For this effort the number of time bins and bin length utilized to estimate and predict link travel times are selected based on experienced gained in initial model development. However, it is readily recognized that these assumptions can significantly influence the ATIS performance and thus should be further studied in future analysis. It is anticipated that no single set of bin parameters (i.e., number utilized and length) will be found to hold, with the best parameters likely of function of the given network size and structure and the desired robustness of the travel time estimates. In this effort four time bins, 180 seconds per bin, are utilized for travel time estimation and prediction.

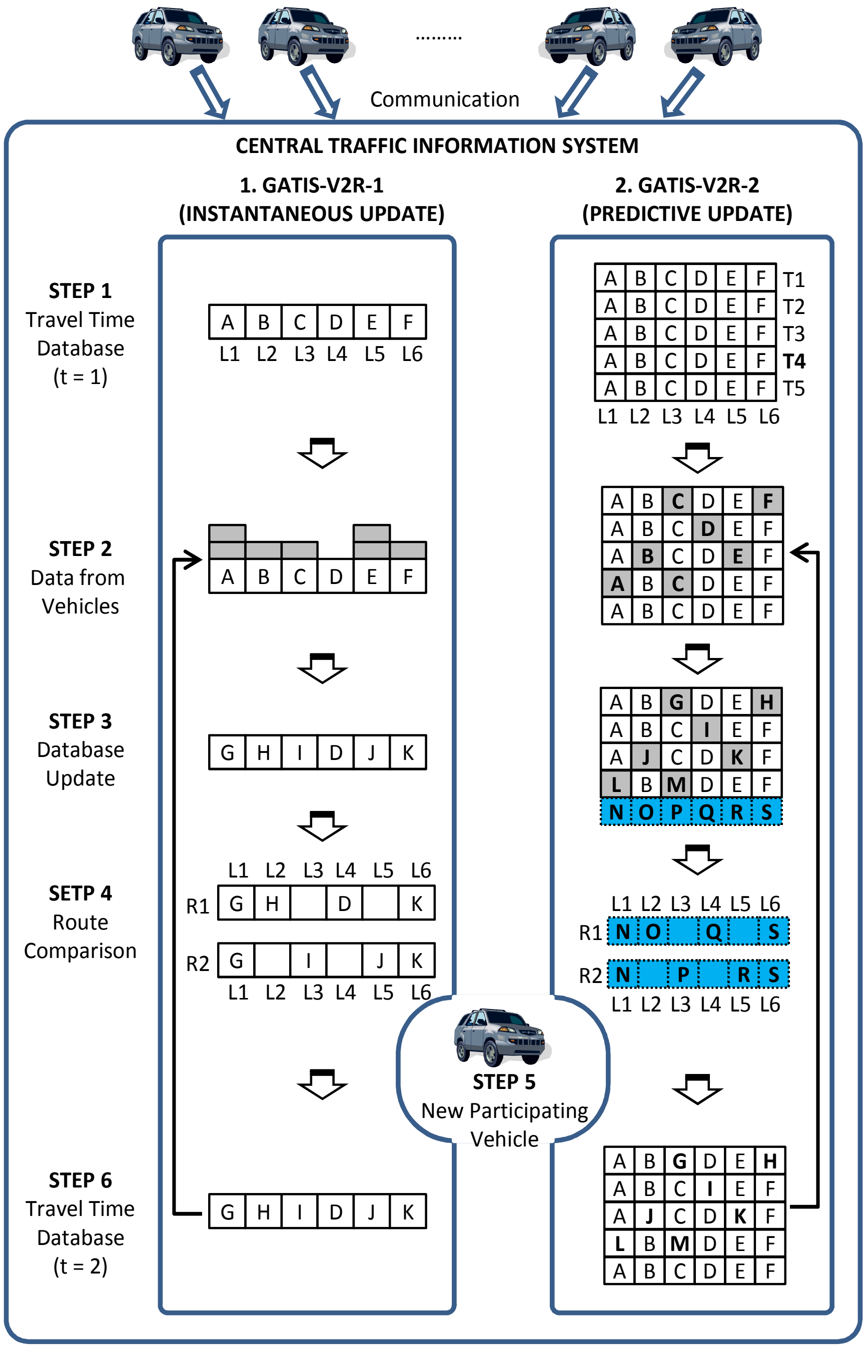


Figure 14: Concept of Traffic Database Update Method in the GATIS-V2R Model

Note: Alphabet in the white cell = historical link travel time / Alphabet in the gray cell = updated link travel time / L# = link number / R# = route number / T# = time bin

C) Database Update – the GATIS-V2V (Decentralized ATIS)

As seen in the previous chapter the database update method in the GATIS-V2V model is similar to that of the GATIS-V2R model-2. The primary difference is that each vehicle autonomously executes database updates and route selection on-board the vehicle, utilizing received data. Thus, in the GATIS-V2R model the central database is assumed to receive data from all vehicles in the network while in the GATIS-V2V model a vehicle will only have that data that has been received through the V2V data communication between participating vehicles.

4.2.3 Route Update

In the current implementation the GATIS-V2R and GATIS-V2V models apply different route update schemes. In the GATIS-V2R model at each update interval the travel time is calculated for each route in the network based on the current centralized link travel time database (Figure 14, Step 4). As each new vehicle enters the network its route is selected based on the current route travel times (Step 5). A vehicle currently in the network is not sent an updated route based on updates that may occur in the centralized database during that vehicle's trip. Essentially, this is the equivalent of travelers checking the traffic conditions at the start of their trip and using that information to make their route selection (e.g., picking your route to work based on the reported traffic conditions when you leave your house). It is assumed that after beginning their trip the travelers receive no new traffic reports that might cause them to change routes.

Route update process in the GATIS-V2V model is different from that of GATIS-V2R model in that the travel time databases reside on the vehicles themselves and at the end of each time bin (3 minutes in the current implementation) each participating vehicle will recalculate the optimal route from its current position to its final destination (Step 4). If this route is different from the vehicle's current route the vehicle will change routes (Step 5). This is equivalent to a traveler selecting their initial route to work but receiving new information during their trip (e.g., from a radio traffic report) and changing their route based on that data. It is noted that small differences in the travel time between routes can trigger unnecessary re-routing. Therefore, a minimum time savings threshold is applied for a vehicle to choose a new route [80]. In this experiment a 10-second time threshold is utilized. It is recognized that the appropriate value for such a threshold will likely be highly dependent on the configuration of the network under consideration. This issue is reserved for the later introduction of boundedly rational switching to the GATIS-V2V model.

4.3 Experimental Design

A simple VISSIM traffic network is utilized, as seen in Figure 15. All links are one-way, from the left to the right, with every vehicle entering at the leftmost network node and exiting at the right most network node. Vehicles are generated at the leftmost node at constant headways according to the desired traffic flow rate. The desired speed of generated vehicles is 48kph. Upon generation each vehicle is assigned as a participating or non-participating vehicle based on the desired participation rate (i.e., penetration ratio). Each participating vehicle is also assigned an initial route through the network as described in Section 4.2.3 while each non-participating vehicle is assigned a route through the network randomly. In this example two routes are possible; the upper set of links (link 1 to link 2 to link 4 to link 6) or lower set of links (link 1 to link 3 to link 5 to link 6). The non-congested travel time of the two routes is approximately equal.

The departing link (link 6) is a two-lane road minimizing possible vehicle conflicts at the link 4/link 5 merge. Also, the length of the entering link (link 1) is set such that during the GATIS-V2V model run the length of at least one time bin will pass while the vehicle is on the link. This ensures that the vehicle will undertake the route choice decision process at least once prior to the decision point at the link 2/link 3 split. Each simulation experiment is run for 3600sec, with the reported results the average of ten replicates. System update time interval (i.e., database time bin) is an important factor for timely update of traffic state with sufficient traffic information, which is set to three minutes in this experiment.

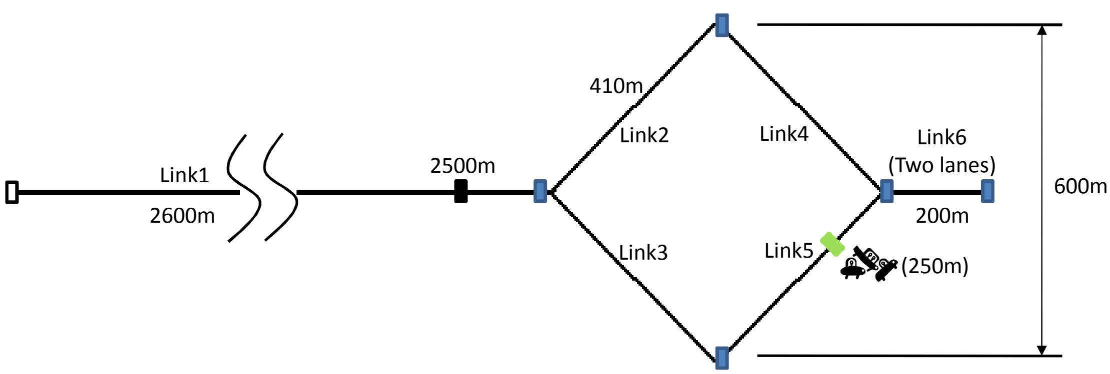


Figure 15: Layout of Notional Traffic Network

Table 4 provides the legend for locations identified in Figure 15 where link travel time data is collected or vehicles select or update their route choice.

Table 4: Functional Network Information

Symbol	Activity	Function	Time	Vehicle Type	ATIS Model
	Vehicle entry	Vehicle generation	Constant headway based on flow rate	P*, NP**	GATIS-V2R-1, GATIS-V2R-2, GATIS-V2V
		Route selection	On new vehicle generation	P, NP	GATIS-V2R-1, GATIS-V2R-2
	Final route selection	Last location at which selected route may change	At presence of vehicle at location	P	GATIS-V2V
	Detector	Record upstream link travel time	At presence of vehicle on detector	P	GATIS-V2R-1, GATIS-V2R-2, GATIS-V2V
	Incident location	Creates bottleneck, increasing travel time on link.	1000sec to 2000sec with one vehicle release per 90sec	P, NP	GATIS-V2R-1, GATIS-V2R-2, GATIS-V2V

Note: * = participating vehicle, ** = non-participating vehicle

The sensitivity of the models to three underlying system parameters is considered in these experiments (Table 5). For brevity the reported results in this chapter are drawn from the 720vph traffic flow scenarios, however, similar trends are seen in the 300vph and 514vph experiments. In addition, to examine the performance of the proposed ATIS models under various traffic states a traffic incident is modeled on link 5. The traffic incident is in effect from 1000sec to 2000sec, releasing vehicles at a rate of 1 every 90seconds.

Table 5: Factors Parameter Ranges Studied

Parameter	Range	Involved ATIS model	Note
Traffic flow	300, 514, and 720vph	GATIS-V2R-1, GATIS-V2R-2, GATIS-V2V	12, 7, and 5 seconds respective constant headway
Communication radio range	300, 400, and 500m	GATIS-V2V	Omni-directional and no signal interference
Penetration ratio	10% to 100%	GATIS-V2R-1, GATIS-V2R-2, GATIS-V2V	10% increment

4.4 Results and Analysis

It is anticipated that for each of the ATIS models under study as traffic flow rate, communication radio range, and penetration ratio increase, a higher percentage of participating vehicles will be afforded the opportunity to re-route should an alternate path provide a lower travel time. The following analysis attempts to confirm this expectation as well as determine the efficiency of each approach in providing participating vehicles with accurate data in a sufficiently timely manner that it may be used for routing decisions.

It is noted that the current experimental design is intended for initial exploration of the proposed architecture. As such the volume scenarios are selected such that sufficient excess capacity exists on each route and that vehicle re-routing will not result in a notable increase in travel time on the new routes. Thus, the impacts of driver route changes (i.e., a sufficient number of drivers changing routes such that the new route breaks down) is not captured [80, 105]. In addition, complete driver compliance is assumed, that is, drivers change routes whenever a shorter path becomes available and there is no subset of drivers who choose to remain on their chosen route regardless updated travel time information. Thus, participating vehicles are assumed to use a greedy optimization with the probabilistic tendencies of some drivers changing routes and others not only reflected by use of the penetration ratio [106].

4.4.1 The GATIS-V2R-1 and GATIS-V2R-2 Route Travel Time

To gain a general sense of the GATIS-V2R models behavior Figure 16 displays the GATIS-V2R-1 and GATIS-V2R-2 upper and lower route travel times for a single replicate run of the scenario with an entering traffic volume of 720vph and a penetration ratio of 100%. The impact of the incident is clearly seen on the lower route in both methods. The incident impact is first noted at approximately 1260 seconds, 260 seconds after the start of the incident. This delay results from a participating vehicle not sending an updated travel time to the traffic information center until it successfully traverses the subject link. Thus, within 260 seconds after the incident initiation the first participating vehicle successfully passes through the incident and completes its traversal of link 5. Therefore, from time t = 1000 seconds to t = 1260 seconds participating vehicles may continue to select the lower route, unaware of the incident. The impact of this delayed identification of the incident in the database is seen in the increasing travel times reported from time t = 1260 seconds until slightly after the incident clearance at t = 2000 seconds. These travel times are from vehicles already on the lower route when the incident occurred with those that enter the route between t = 1000 seconds and t = 1260 seconds, unaware of the incident. After approximately t = 1260 seconds no additional participating vehicles enter the lower route under either the GATIS-V2R-1 or the GATIS-

V2R-2, as the upper route travel time is reported as lower. In the GATIS-V2R-1 model vehicles will not enter the lower route anytime during the remaining simulation run. As the last reported travel time is reported as the current estimate for links in which no data is reported even well after the incident clears the route travel time will continue to be as high in the GATIS-V2R-1 model. This link will not be traversed by a participating vehicle therefore no after-incident travel time will be sampled to allow for a reduced estimated travel time. In contrast, the GATIS-V2R-2 method will eventually allow for participating vehicles to traverse the lower route as any time bin with no travel time data reported will utilize historical travel time data, which is the non-incident travel time. Thus, after four time bins pass without a travel time reported the estimated travel time will again be the non-incident travel time.

It is noted that the GATIS-V2R-2 model estimated lower route travel time is consistently lower than the GATIS-V2R-1 model travel time during the incident period. This is a result of the averaging in the GATIS-V2R-2 model method, where in this incident scenario the actual travel time is continuously increasing during the incident duration. However, the vehicles experience the same travel time in both methods.

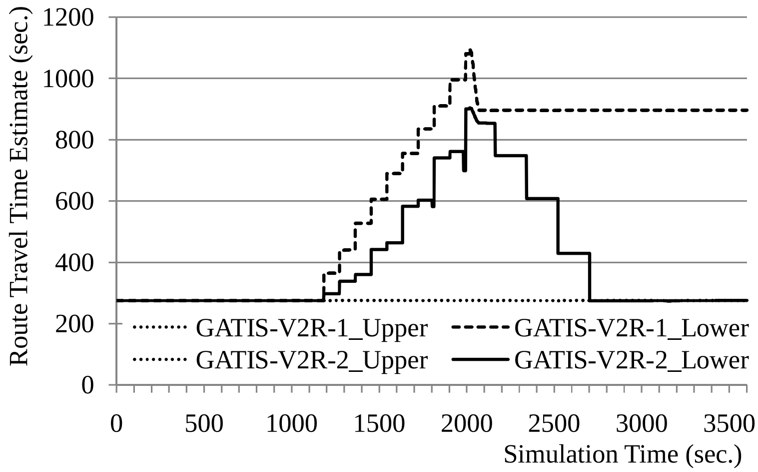


Figure 16: Route Travel Time Estimate Comparison in GATIS-V2R Model

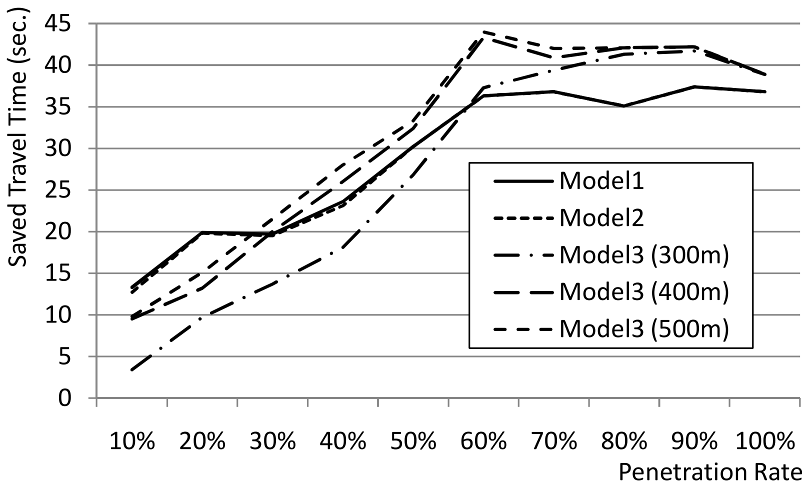
4.4.2 Average Travel Time Difference of Participating and Non-participating Vehicles

Figure 17 shows the average travel time difference between the base scenario (i.e., no vehicle re-routing) and the developed ATIS models and Coefficient of Variation (CV) (i.e., standard deviation / mean) of simulation outputs, for an entering traffic demand of 720vph over penetration ratios ranging from 10% to 100%. At low penetration ratios and short radio ranges high travel time saving variance is identified for participating and non-participating vehicles, with standard deviations exceeding the mean savings (i.e., CV greater than 1) at the lowest levels (i.e., 10% and 20% penetration). This indicates that at the lower penetration rates the travel time savings under all systems is unreliable. As the penetration ratio increases the CV decreases, providing for a higher reliability in the travel time savings. Similar results are seen for the lower demand scenarios, however, higher penetration rates are needed to lower the CV as the number of participating vehicles in a system is a function of both the penetration rate and overall demand.

It is seen that the travel time of participating vehicles in all ATIS models tend to be lower than that of the base scenario (Figure 17 (a)). Furthermore, as expected, as the penetration ratio increases the travel time savings increase. At a penetration ratio of approximately 60% the average travel time savings and CV of participating vehicles stabilizes, implying a limited marginal benefit to currently participating vehicles with the addition of more participating vehicles in the fleet. It is also noted that the non-participating vehicles receive some benefit (Figure 17 (b)), as participating vehicles are able to avoid the incident, reducing the overall demand at the incident location and subsequent incident related congestion. Also, as there are fewer non-participating vehicles in the network as the participating vehicle penetration ratio increases the number of vehicles on the incident link decreases, reducing the overall incident impact.

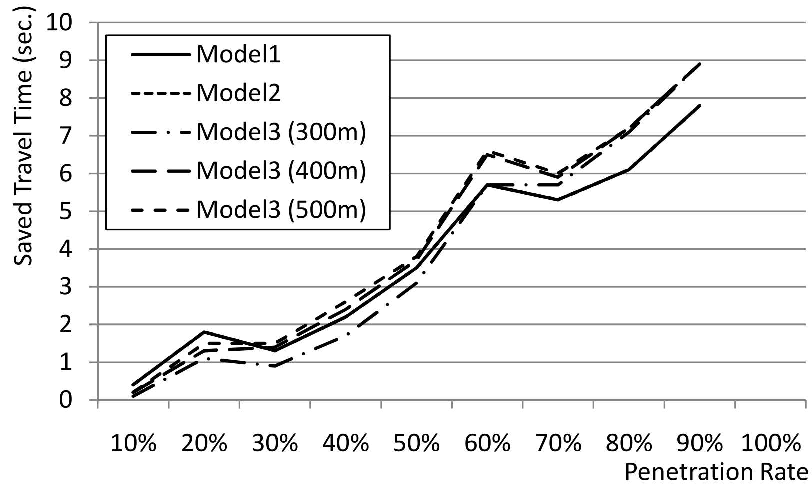
It is observed that the GATIS-V2R-1 and GATIS-V2R-2 models provide nearly identical time savings. However, it is noted that the GATIS-V2R-1 model results in a higher number of participating vehicles that are re-routed during the simulation period. This is a result of the method used by each model to impute the travel time for a link when no data has been received for the respective update interval or time bin, as discussed in Section 4.4.1. As the lower route travel time never returns to the non-incident travel time in the GATIS-V2R-1 model the vehicles will continue to be re-routed even after the incident has cleared. If the non-congested travel times of the two routes were not similar this behavior could significantly impact the travel time benefit of the GATIS-V2R-1 model. While not reflected in the travel time findings of this study this inability to update travel time information on routes without participating vehicles represents a potentially significant limitation in instrumented vehicle only ATIS based systems.

Finally, as expected, as the radio range in the GATIS-V2V model increases the travel time savings improve. However, it is interesting to note that at lower penetration ratios the GATIS-V2R models provide greater travel time savings while at the higher penetration ratios the GATIS-V2V models provide higher savings. This is a reflection of the trade-offs between the two methods. At lower penetration ratios information passing is less efficient in the GATIS-V2V model (as message hopping opportunities are fewer), resulting in the on-board databases having incomplete data. As the penetration ratio increases the dynamic communication network becomes increasing robust with participating vehicles receiving an increasing percentage of the available travel time data. However, the GATIS-V2R model database will contain the data from all participating vehicles regardless of the penetration ratio. Thus, at lower penetration ratios the GATIS-V2R model approach is able to make more informed decisions. However, the GATIS-V2V model has an inherent advantage in that a vehicle may change its route while in the network. Thus, as the penetration ratio increases the GATIS-V2R model advantage is lessened and the GATIS-V2V model mid-trip re-routing capabilities become increasingly advantageous, ultimately providing greater travel time savings at higher penetration ratios.



	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Model1	1.5	0.9	0.6	0.3	0.3	0.3	0.1	0.2	0.2	0.1
Model2	1.6	0.9	0.6	0.6	0.3	0.3	0.1	0.2	0.2	0.1
Model3 (300m)	2.4	1.0	0.8	0.5	0.5	0.4	0.3	0.3	0.3	0.3
Modle3 (400m)	1.7	0.9	0.8	0.6	0.4	0.4	0.2	0.3	0.3	0.3
Model3 (500m)	1.7	0.9	0.8	0.6	0.4	0.4	0.2	0.3	0.3	0.3

(a) Travel time savings and Coefficient of Variation for participating vehicles



	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Model1	1.3	1.0	0.6	0.5	0.4	0.4	0.3	0.4	0.2	NA
Model2	1.3	1.0	0.6	0.5	0.4	0.4	0.3	0.4	0.2	NA
Model3 (300m)	2.4	1.3	0.9	0.4	0.5	0.4	0.4	0.4	0.4	NA
Model3 (400m)	1.7	1.2	0.8	0.4	0.5	0.4	0.4	0.4	0.4	NA
Model3 (500m)	1.6	1.1	0.8	0.5	0.4	0.4	0.4	0.4	0.4	NA

(b) Travel time savings and Coefficient of Variation for non-participating vehicles

Figure 17: Average Travel Time Savings Comparison and Coefficient of Variation (720vph Flow Rate Scenario)

Note: Model1 = the GATIS-V2R-1 model, Model2 = the GATIS-V2R-2 model, Model3 = the GATIS-V2V model

4.4.3 Long-term Accident Case

As seen in Section 4.4.1 this study presents the performance of the developed GATIS-V2R-1 and GATIS-V2R-1 models given a realtively short-term traffic incident. However, given the observed behavior it is natural to investigate how the developed models would respond to a more significant incident. Thus, a longer incident duration experiment was designed as outlined in Table 6. The resulting route travel times for the GATIS-V2R models is shown in Figure 18.

Table 6: Simulation Parameters for Long-term Traffic Incident Case

Parameter	Value
Simulation time	7200sec
Traffic incident	From 1000 to 6000sec
Traffic flow	300vph
Penetration ratio	100%
Involved ATIS models	GATIS-V2R-1 and 2

As the GATIS-V2R-1 model utilizes the last recorded link travel time for links where no travel time is reported for an update interval the lower route travel time estimate is constant after the last participating vehicle assigned to the lower route exits the incident location at approximately 1800 seconds. However, the GATIS-V2R-2 model utilizes historical non-incident data when no new data is available. Thus, for the given GATIS-V2R-2 model parameters, 12 minutes after the participating vehicle at time 1800 seconds departs the incident location the impact of the incident on travel time is removed completely from the travel time database. This will result in a participating vehicle potentially selecting the lower route, even though the incident still exists, as witnessed by the second increase in travel time on the GATIS-V2R-2 model lower route starting at approximately 3000 seconds. This is the same behavior that would be witnessed with the GATIS-V2V model. Once a participating vehicle successfully traverses the incident location the GATIS-V2R-2 (or GATIS-V2V) model travel time database is again informed of the incident and participating vehicles again start re-routing around the incident. The behavior of both the GATIS-V2R-1 and GATIS-V2R-2 models highlight a significant drawback to an ATIS system based solely on participating vehicle data. That is, some subset of participating vehicles must traverse each link to maintain reasonable travel time estimates. Otherwise, participating vehicles will continue to avoid links, reducing system efficiency, well after an incident has cleared (e.g., the GATIS-V2R-1 model lower route travel time estimate in Figure 16) or vehicles will be required to "probe" the previously congested link to determine if the incident still exists, potentially requiring a participating vehicle to use a highly inefficient route (e.g., the GATIS-V2R-2 model lower route travel time estimate in Figure 18).

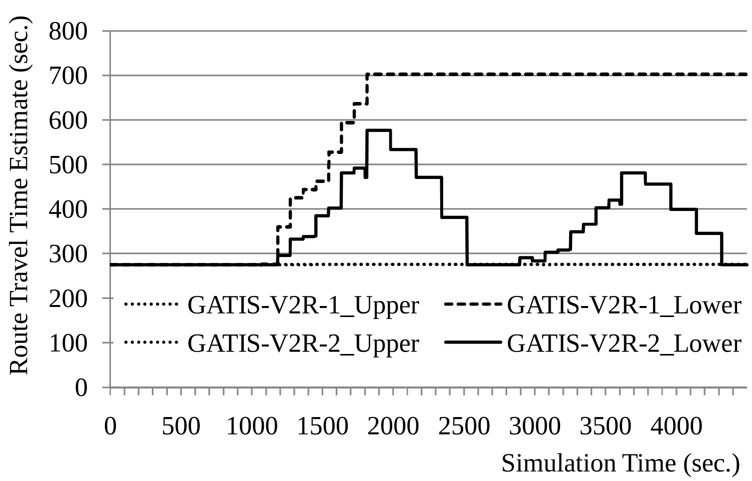


Figure 18: Route Travel Time Estimate Comparison in the Long-term Traffic Incident Case

4.5 Summary

This chapter introduced the fundamental framework of an ATIS model using V2V and V2R communication systems under decentralized and centralized data processing assumptions, respectively. Key factors on the performance of ATIS model using V2V and V2R communication systems on a simple traffic network were investigated with an off-the-shelf microscopic simulation model, VISSIM, assuming an ideal communication environment. In this ATIS DRGS implementation travel time information is stored in STM residing in the traffic information center (the GATIS-V2R models) or on-board each participating vehicle (the GATIS-V2V model). Participating vehicles communicate travel time updates with roadside units or neighboring participating vehicles. Using the travel time data gathered the central database or on-board databases are updated, allowing for the calculation of revised routing information.

Through the experiments it was noted that there is some delay between the incident start and its effect influencing the GATIS-V2R model or GATIS-V2V model route travel time estimates. The delay resulted in some participating vehicles not receiving updated travel time estimates in a sufficiently timely manner to allow them to avoid the incident-related congestion. That is, that some subset of participating vehicles must traverse each link to maintain reasonable travel time estimates. Otherwise, participating vehicles will continue to avoid links, reducing system efficiency, well after an incident has cleared or vehicles will be required to "probe" the previously congested link to determine if the incident still exists, potentially requiring a participating vehicle to use a highly inefficient route (the GATIS-V2R-2 model). However, even with these drawbacks all three proposed system were seen to provide travel time saving benefits to both participating and non-participating vehicles. In the mid and higher range volume scenarios the GATIS-V2V provided equal or better performance as that of the GATIS-V2R. It is only in the low demand scenario were the GATIS-V2V is unable to create sufficient communication groups to effectively pass the data that the GATIS-V2R proves a superior approach. Chapter 5 delves more deeply into the GATIS-V2V system, investigating the impact of the three proposed enhancements. In order to investigate more general system characteristics and improve the system performance the developed GATIS-V2V and GATIS-V2R ATIS models will be implemented and tested on the signalized traffic network (Chapter 6) and a larger and more complicated traffic network, representing a more realistic set of route choices, in the Chapters 7 and 8.

CHAPTER 5 GATIS-V2V MODEL ENHANCEMENTS IN NON-SIGNALIZED SIMPLE NETWORK

5.1 Introduction

Chapter 4 introduced two types of traffic information system (i.e., GATIS-V2V and GATIS-V2R models) and database management strategies with an assumption that drivers do not change their routes as a result of a small discrepancy (i.e., 10 seconds) in the travel time between the system-guided and the existing routes in the notional small network. Chapter 5 investigates issues inherent in the basic GATIS-V2V model and implements and evaluates three system enhancing functions.

As stated earlier, DynaMIT and DynaSmart are the typical examples of DRGS as simulation-based DTA systems. However, the DTA model operated in the traffic center (i.e., centralized DTA (CDTA)) demands intensive computational resources and significant predictive input information for large networks, leading to nontrivial time lags between a non-recurrent traffic event occurrence and responsive traffic strategy generation [107-109]. Hawas and Mahmassani proposed a decentralized DTA (DDTA) which is spatially distributed and more frequently updates vehicle routes, relying on limited and locally available traffic information [107]. Chiu and Mahmassani developed a hybrid DTA (HDTA) interplaying between a CDTA and a DDTA [108, 109]. They concluded that DDTA and HDTA are more robust under incident conditions than CDTA. They also stressed that demand prediction error due to inaccurate data and stochasticity in driver behavior are the most sensitive factors affecting model performance.

The GATIS-V2V model is a counterpart of DTA, operated in the decentralized fashion. Most research on ATIS using V2V communication focuses on the original model development [85, 88, 110] or investigation of the system-wide sensitivity of three underlying system parameters to model performance under various research-dependent scenarios [52, 111, 112]. However, in order for the model to be more efficient and robust commonly highlighted DTA research issues (i.e., early detection of non-recurrent traffic states, data accuracy, and driver behavioral rule) should be addressed in the GATIS-V2V model.

This chapter aims not only to identify the critical issues in the GATIS-V2V model but also to implement three system-enhancing functions to help mitigate their effects. ATIS model performance is investigated on the same simple notional traffic network as in Chapter 4 in an attempt to explore the feasibility of the integration of such ATIS architecture in a commercial simulation, understand the basic operational characteristics of the approach, and find appropriate parameter values for more efficient implementation. Future investigations will provide more in depth analysis, exploring the different facets of the architecture on a larger traffic network.

5.2 Experimental Design

This set of experiments utilizes the same VISSIM traffic network and traffic states as in Chapter 4. In brief, the link 1 is sufficiently long to guarantee at least one route update opportunity for participating vehicles prior to the route decision point. The same non-recurrent traffic state (traffic incident) is applied on link 5 from 1000sec to 2000sec with one vehicle release every 90seconds. The Simulation is run for 4600sec and simulation output is measured after 1000sec (warm-up time). Ten replicate runs are utilized for the development of performance measures. The same O-D and route information as in Chapter 4 are utilized. Unlike the previously conducted experiments the basic GATIS-V2V in this experiment allows participating vehicle re-routing given any travel time difference between possible routes (i.e., the 10 second constraint in Chapter 4 is relaxed). Scenarios are generated for traffic demands of 300vph, 514vph, and 720vph, communication radio ranges of 250m, 375m, 500m, and 625m with omni-directional signal emission and no signal interference, and penetration ratios from 0% to 100% in 20% increments.

The experimental design allows for the determination of the impact of each individual proposed enhancing function as well as the combined effects. Eight different GATIS-V2V models composed of one or more of the three system-enhancing functions are designed and evaluated. The default value of each key function is discussed below and Table 8: presents the considered functions for each ATIS model (hereafter referred to as case name in Table 8).

A) AAID function: user-defined congestion factor, $K = 3$

As previously discussed, the Autonomous Automatic Incident Detection (AAID) allows a means for a participating vehicle on a link impacted by an incident, (e.g., experiencing unexpected delay) to notify other participating vehicles prior to the affected vehicle departing the link. The determination of a delay as "unexpected" based on a parameter

(K) in the AAID algorithm. If the vehicle's current time on the link is greater than or equal to the historical travel time multiplied by K then the affected vehicle will send a incident detection message in the next time interval and all subsequent time intervals where the conditions holds. For example, if K is set to 1 than a vehicle would issue an incident message whenever its travel time reaches or exceeds the historical travel time. For the initial analysis K is set to 3, that is, when a vehicle's current travel time exceeds the historic travel time by a factor of 3 an incident message will be sent. It is recognized that this K value is relatively arbitrary, based on first cut exploration into determining a K factor that balances quickly identifying incidents while limiting false alarms. Chapter 6 will delve into the sensitivity of the model the K value.

B) Sample size function: minimum number of travel time records for each link = 2

The sample size function attempts to minimize the impact of a single or small number of false data points. It implement this function a long-term simulation run of the simple network under normal traffic conditions was conducted. Table 7 indicates that the p-values from Shapiro-Wilk normality test for all links are less than 0.05, which means that normality hypothesis for link travel time is rejected with 95% confidence [75]. Thus, the heuristic method is utilized to generate the minimum sample size, which for this network results in a minimum sample size of 2.

Table 7: Descriptive Statistics of Travel Time and Minimum Sample Size

Link #	Mean (sec.)	Standard deviation (sec.)	Normality Test, P-value	Sample Size
1	195	0.21	< 0.0001	2
2	32	0.19	< 0.0001	2
3	32	0.19	< 0.0001	2
4	32	0.17	< 0.0001	2
5	32	0.18	< 0.0001	2
6	15	0.25	< 0.0001	2

C) Driver behavioral rule function

The driver behavior rule function attempts to more realistically reflect driver behavior by only allowing participating vehicles to switch routes when the travel time of an alternate route offers at least 20% travel time savings [79-81]. As discussed in Section 4.2.3, a minor travel time difference between an alternate and current route can cause un-necessary re-routing. Such re-routing does not realistically reflect the real world as most drivers utilize their habitual routes unless a significant savings may be realized. Since this factor is directly related to the update time of the non-recurrent traffic state, it is very important to set it to reasonable value, so the sensitivity of system performance to this parameter is investigated in Chapter 6.

Table 8 Eight GATIS-V2V Models and Considered Parameters

Case No.	Congestion alert system	Sample size	Behavior model	Case name
1	No alert system	> 0	> 0	NABC
2	3	> 0	> 0	A
3	No alert system	> 2	> 0	B
4	No alert system	> 0	> 20%	C
5	3	> 2	> 0	AB
6	3	> 0	> 20%	AC
7	No alert system	> 2	> 20%	BC
8	3	> 2	> 20%	ABC

5.3 Results and Analysis

5.3.1 Problem Identification with the Basic GATIS-V2V Model

Figure 19 presents the average travel time savings per participating vehicle in Case NABC (i.e., no enhancing functions) with varying communication radio range and penetration ratio at a 300vph demand. It is seen that these results indicate a potential issue at high penetration ratios and large radio ranges. It can be anticipated that longer radio range and higher penetration ratio would save more travel time, but interestingly Figure 19 indicates that 250m radio range saves more travel time at 100% penetration ratio than other longer radio range Cases. To understand behavior recall that the theoretical vehicle headway after passing link 1 is 24-second (based on a 300vph flow rate), which corresponds to 320m distance between vehicles. Thus when the radio range exceeds 320m, and the penetration ratio is 100%, all vehicles in the network consistently comprise of single communication group. With no incident detection algorithm there exist some delay between the start of the incident and the incident being reflected in the on-board databases. During this delay period some vehicles may switch from the upper route to the lower route in an attempt to save a few seconds, based on received travel data base updates, and unknowingly entering the incident link and encountering significant additional delay. However, the communication connection in ATIS with 250m communication radio range is easily broken resulting in participating vehicles primarily relying on historical link travel time, which does not show an few second advantage to the lower route, and thus no vehicles switch routes in an attempt to save a few seconds. It is clearly recognized that these results are specific to the network and traffic scenario tested, however, they do demonstrate a scenario were dynamic traffic information may worsen system performance. (In Chapter 6 an incident will be placed on the upper link, allowing for an exploration of the impact of incident location.) In this particular case due to a lag in the information update in representing real-time conditions. This type of scenario provides a clear motivation to adopt enhancing functions into the basic GATIS-V2V model. To explore these enhancing functions Section 5.3.2 presents the impact of traffic incident detection time on the system performance and Section 5.3.3 presents the impact of the number of travel time records reflecting up-to-date traffic state and that the interpretation of individual travel times are very important to route information reliability.

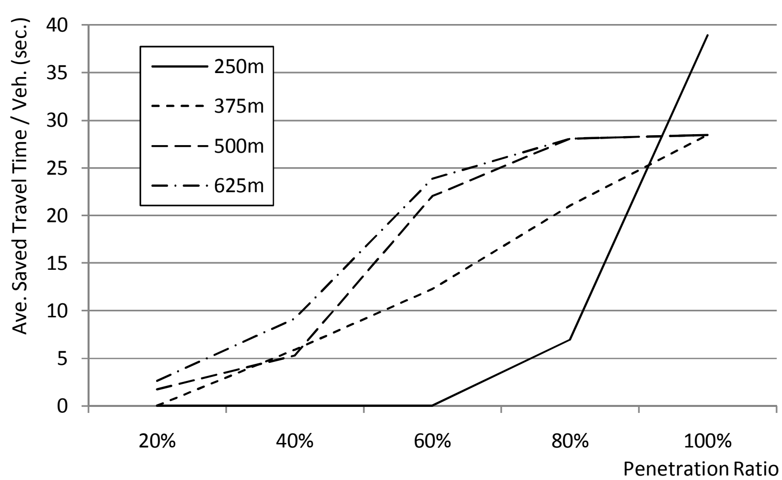
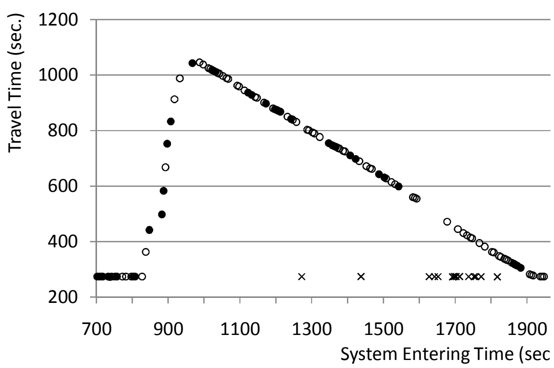


Figure 19: Travel Time Savings of Participating Vehicles, Case NABC

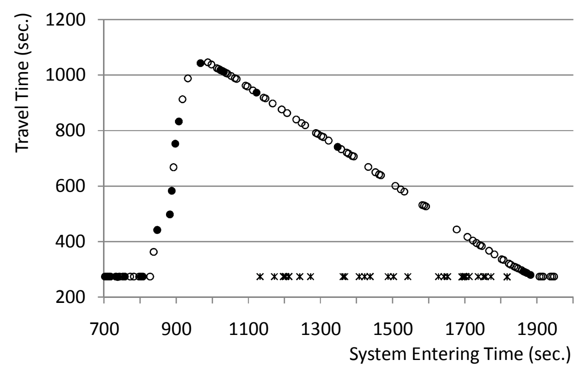
5.3.2 Traffic Incident Detection Time Effect

Figure 20 depicts vehicle travel time along the lower route for four scenarios to highlight the congestion detection time effect. The average travel time for the upper and lower routes is approximately 274-second for free-flow traffic condition. Each sub-figure in

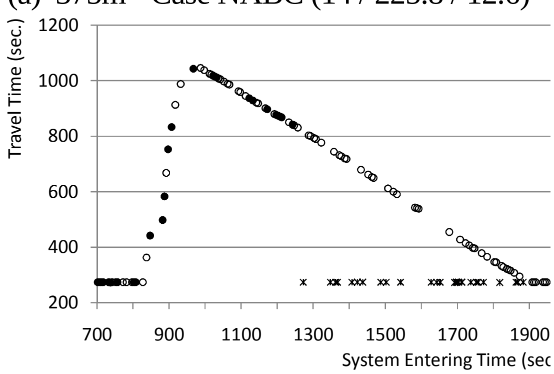
Figure 20 observes vehicle travel time based on the system entering time and compares the no communication model and ATIS model of interest. Figure 20 presents the travel time data for 720vph, 40% penetration ratio, and 5th simulation run for different radio ranges considered. Figure 20 (a) shows the route switch pattern in Case NABC with 375m radio range. After the traffic incident occurs on link 5 at 1000-second, several participating vehicles (black dot) entered the resulting incident-related queue. Case NABC cannot detect traffic congestion until the first participating vehicle in the congestion queue is released and departs the congested link. From this position updated congested link travel time cannot directly reach beyond the route diverting point at any of the tested radio ranges. Figure 20 (b) indicates the re-routing pattern in Case A with 375m radio range. When their time on the link exceeded the alert travel time (K is set to 3 in this example) they issued the congestion alert. The 375m radio range is not sufficiently large for a vehicle in the incident-related queue to communicate directly with vehicles upstream the route diverting point (2500m point on link 1), requiring message hops to transmit the message, creating some delay between the issuing of the alert message on the re-routing of participating vehicles from the downstream route. Some participating vehicles continue to enter the lower path after the alert is initially sent. At the larger radio range of 625m in Figure 20 (c) participating vehicles start re-routing earlier than the Case NABC at 375m but still do not achieve earlier re-routing time of the Case A with the shorter radio range of 375m. Figure 20 (d) depicts re-routing result of Case A with the larger radio range 625m, showing the best performance overall, with the earliest re-routing after incident occurrence. This type of ATIS model can update congestion faster and enable more vehicles to bypass the congestion area. Thus, the trade-off is seen between increased confidence in the traveler time data and the potential of delaying the response to accurate, but limited, information. Clearly, the efficiency of ATIS model using V2V (travel time savings in Figure 20 (a) ~ (d)) is dependent on how quickly the non-recurrent traffic state can be detected and transmitted to vehicles that have alternate routes available.



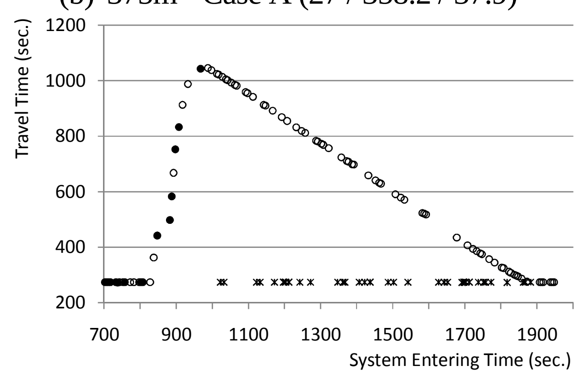
(a) 375m - Case NABC (14 / 225.8 / 12.6)



(b) 375m - Case A (27 / 358.2 / 37.9)



(c) 625m - Case NABC (25 / 268.7 / 25.8)



(d) 625m - Case A (34 / 367.8 / 48.1)

Figure 20: Effect of the Incident Detection Time on the System Performance (720vph, 40% Penetration Ratio, and 5^{th} Run)

Note: black dot = participating vehicles / white dot = non-participating vehicles / cross mark = participating vehicles re-routing from the lower to the upper route / (# / ## / ###), # = number of re-routing vehicles due to traffic incident, ## = average travel time savings of incident-involved participating vehicles, #### = average travel time savings of all participating vehicles

5.3.3 Travel Time Comparison of Various GATIS-V2V Models

Figure 21 shows the average travel time difference between the no vehicle re-routing model and ATIS models for an entering traffic demand of 720vph over penetration ratios ranging from 0% (i.e., no-communication model) to 100%, in 20% increment. It is seen that the travel time of participating vehicles in all ATIS models tend to be lower than that of the no-communication model (Figure 21 (a) and (c)), except the Case BC. This except is a function of the experimental design. Under the incident condition one vehicle is released every 90 seconds from the incident. Thus, travel time data from more than two participating vehicles will never be available to update the travel time database for one system update time interval (i.e., 3 minutes). Therefore, the route travel times updated based on the historical link travel time cannot exceed the 20% traffic time difference between the alternate and the current route. Furthermore, as expected, at lower penetration ratios information dissemination is less efficient (as message hopping opportunities are fewer) resulting in lower average travel time saving. As the penetration ratio increases the dynamic communication network becomes more stable and higher travel time saving are realized. At a penetration ratio of approximately 60% the average travel time savings stabilizes, implying a limited marginal benefit to the currently participating vehicles with the addition of more participating vehicles in the fleet. It is also noted that the non-participating vehicles receive some benefit (Figure 21 (b) and (d)), as participating vehicles are able to avoid the incident, reducing the overall demand at the incident location and subsequent incident-related congestion. It is also noted that as the radio range increases the travel time savings improve at a faster rate for the lower penetration ratios. However, the maximum savings (approximately 60seconds per participating vehicle) remains similar for both the 375m and 625m radio ranges.

Focusing on ATIS Cases, system performance of each ATIS Case can be interpreted from the fundamental characteristics of each ATIS model.

- Case BC: as already addressed, Case BC resulted in no vehicle re-routings due to the given the sample size requirement (Case B) and need for 20% travel time difference between the system route and current route (Case C, i.e., boundedly rational switching). This demonstrates the potential degradation in system performance when attempting to insure reliable data. However, it is important to note that this test does not include any erroneous data, resulting in the sample size limit consistently degrading performance. In a real-world implementation erroneous data is likely, creating the opportunity for system benefits using the sample size rule. Future efforts will explore the issues of erroneous data.

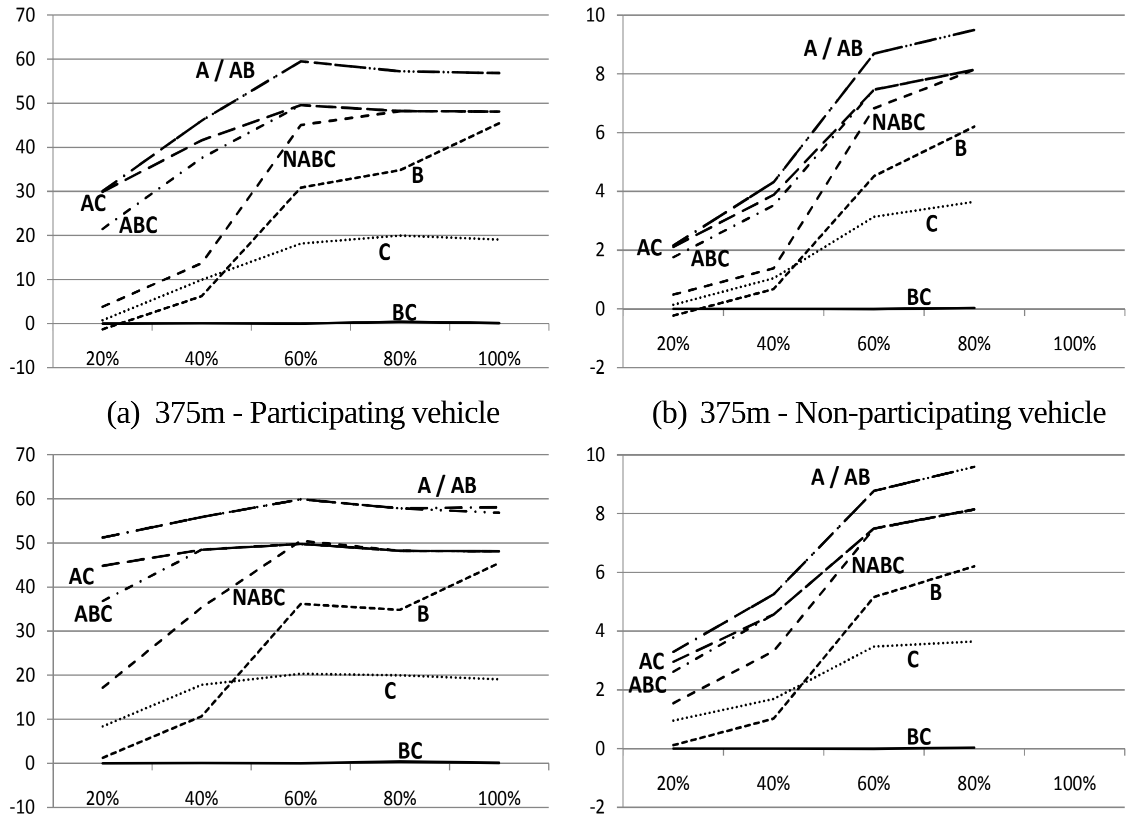
- Case C: Case C updates the traffic incident only once a participating vehicle successfully departs the incident link. This relatively late reflection of the traffic incident in travel times leads to the less efficient model than others cases that include A (the accident detection capability). Also, Case C reflects that a driver’s likelihood of switching to a new route is generally reduced with increasing congestion [78]. Controlling for drivers’ not switching to a new route (i.e., vehicle re-routing) at the small travel time difference results in a model that will more realistically reflect real-world behaviors. Therefore, ATIS models without Case C may be regarded as the less realistic ATIS model.

- Case B: as long as the number of travel time records is over the minimum sample size the vehicle re-routing is executed, even with small travel time difference between routes. As penetration ratios increase, additional travel time data becomes available, thus, the likelihood of exceeding the minimum sample size during a system update time interval increases. However, it is again seen that CASE B consistently provides lower savings that Case NABC. This is a direct result of the desire to improve data reliability delaying the potential immediacy of responding to the incident.

- Case NABC: this case does not have to meet any sample size requirements or the minimum travel time difference rule. Therefore, it has more opportunities to update the travel time database and routes responding to the traffic incident, outperforming Cases C and B. However, as discussed, the system performance is likely less realistic.

- Cases AC and ABC: these are the realistic models coupled with the incident detection capability resulting in higher travel times savings that are more efficient, stable, and reliable. Case A-involved ATIS models explicitly recognize the non-recurrent traffic states and instantaneously update the database and routes. Case C limits unlikely re-routing prior to the incident. The system output is the most robust to any type of traffic states compared to other ATIS models.

- Cases A and AB: these cases re-route vehicles with any small traffic time differences between routes. It is important to note that the accident warning message is not subject to the minimum sample size requirement, thus the impact of the sample size constraint is not seen in case AB. These systems seem to be the most efficient, but they are likely somewhat unrealistic due to early vehicle re-routings. That is, they do not reflect boundedly rational driving behavior.



(a) 375m - Participating vehicle (b) 375m - Non-participating vehicle

(c) 625m - Participating vehicle (d) 625m - Non-participating vehicle

Figure 21: Average Travel Time Savings Comparison with Different ATIS Cases (720vph Flow Rate, 375m and 625m Radio Range Scenarios)

Note: X-axis is the penetration ratio and Y-axis is the average travel time savings

5.4 Summary

This chapter built upon the developed dynamic decentralized ATIS model using the V2V system as an alternative to DTA executed in the traffic center. Three complementary functions (i.e., AAID, sample size, driver behavioral rule functions) were implemented to improve the system efficiency of the basic GATIS-V2V model.

This study identified that dynamic real-time traffic data dissemination under fairly good communication condition (i.e., larger radio range) in the basic GATIS-V2V model

(Case NABC) does not always outperforms ATIS model with less favorable communication conditions because of unreliable data propagation. Also, through the experiments it was noted that there is some delay between the incident start and its effect influencing route travel time estimates. The delay resulted in some participating vehicles not receiving updated travel time estimates in a sufficiently timely manner to allow them to avoid the incident-related congestion. In fact, Figure 20 indicates that shortening the time delay is very important to improve the system performance.

In addition, when comparing eight GATIS-V2V models composed of three complementary functions it has been seen that the drivers' re-routing rule creates (boundedly rational behavior) has a fundamental influence on the system performance, controlling the re-routing patterns before the incident and when combined with the congestion alert system performance is consistent and robust. The congestion alert system also provides the most immediate response to non-recurrent congestion such as an incident. Therefore, Cases AC / ABC create the most realistic and reliable system performance. On the other hand, the system performance of Case B (the minimum sample size rule) is potentially less realistic and less efficient due to route updates continuing to depend on the historical link travel time when limited new data is available, demonstrating the potential trade-off between data reliability and immediacy of response.

As expected, as the penetration ratio and communication radio range increase, the participating and non-participating vehicles save more travel time, over nearly all ATIS system configuration. However, it is seen, that for this example network, there are no marginal benefits (i.e., average saved travel time per vehicle) to a participating vehicle for penetrations rates exceeding 60%. Chapter 6 will investigate more general system characteristics of these various ATIS models in the signalized traffic network and conduct a sensitivity analysis of K and I factors.

CHAPTER 6 EVALUATION OF GATIS-V2V MODEL IN SIMPLE SIGNALIZED NETWORK AND SENSITIVITY ANALYSIS OF *K* AND *I* FACTORS

6.1 Introduction

Chapters 4 and 5 investigated the characteristics and potential issues of the basic and enhanced GATIS-V2V in the simple non-signalized traffic network. However, signalized intersections can greatly increase the variability of the link travel time. Chapter 6 compares the eight GATIS-V2V models configuration explored in Chapter 5 and investigates system reliability and robustness in the signalized traffic network. In order to gain a better understanding of the relationship between the system performance and the proposed enhancements a sensitivity analysis of travel time savings to potential parameter values is conducted.

6.2 Experimental Design

The traffic network used in this chapter is the same as notional network previously used (Figure 15), with the exception that traffic signals are placed at three locations. Also, as part of this analysis model runs are conducted with an incident on the lower route path as well as model runs with an incident located on the upper path (Figure 22). These are exclusive alternatives; an incident is not placed on both the upper and lower path as part of any scenarios currently considered. Figure 23 illustrates the traffic signal timing parameters such as cycle length, offset, and phase at each location. Other experimental parameters include a traffic flow rate of 720vph with an assumed constant vehicle headway of 5 sec., communication radio ranges specified as 375m or 625m, and penetration ratio ranges from 0% to 100% in 20% increments. This section runs the eight GATIS-V2V models under incident conditions (incident occurs from 1000sec to 2000sec) and addresses the characteristics of the GATIS-V2V models observed in the signalized traffic network. For the advanced GATIS-V2V model this study utilizes the same default parameter values from Chapter 5 for the *K* factor (i.e., *K* = 3) and the *I* factor (i.e., *I* = 20%). Furthermore, since the signalized traffic network has dramatically different travel time distributions and patterns link by link, the normality test applied to the replicated trials used to generate the historical data rejected the null hypothesis that travel time data is normally distributed and the heuristic method was then considered for minimum sample size instead of simply using the Equation 1 (Section 3.5.2 A)) (Table 9).

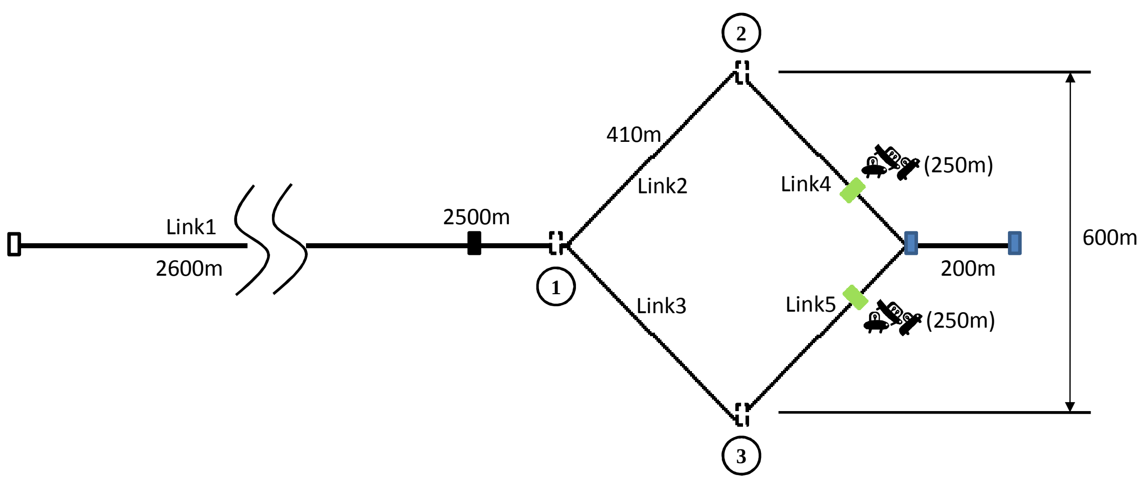


Figure 22: Revised Network Layout with Traffic Signals and another Traffic Incident

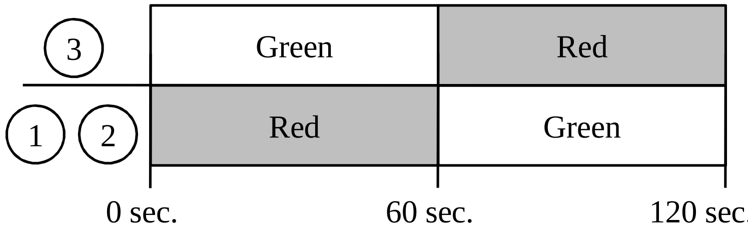
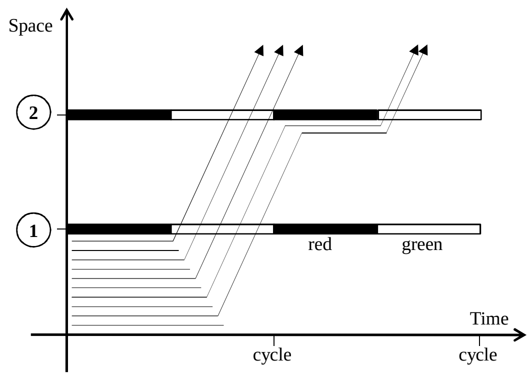


Figure 23: Signal Timing Parameters Considered

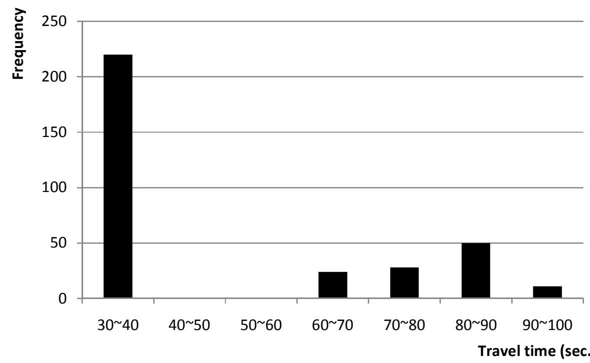
Table 9: Historical Link Travel Time and Minimum Sample Size Information

Link number	Historical travel time	Minimum Sample Size	Route Info.
Link 1	218	2	Upper and lower routes
Link 2	50	14	Upper route
Link 3	53	4	Lower route
Link 4	32	2	Upper route (incident link)
Link 5	32	2	Lower route (incident link)
Link 6	15	2	Upper and lower routes
Upper route travel time	314 seconds		
Lower route travel time	317 seconds		

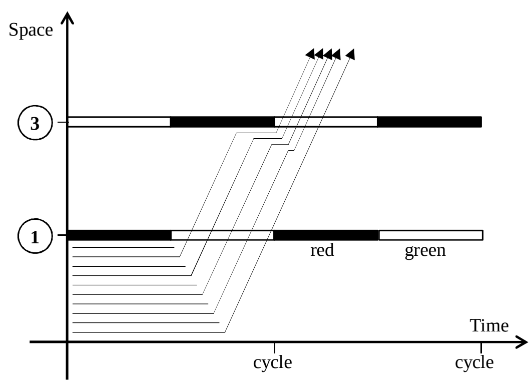
It is noteworthy that an update will not occur on travel time of Link 2 because the minimum sample size (i.e., 14) accounts for 77% of the average maximum number of vehicles (i.e., the upper boundary of the minimum sample size = 18). That is, unless the penetration ratio of the participating vehicles approaches 80%, the system relies on the historical link travel time, not real-time actual traffic information, for the route update. This would result in the ATIS system essentially ignoring the probe vehicle data under nearly all scenarios tested. Clearly, given the variability of traffic flow under signalized conditions the proposed minimum sample size heuristic is too conservative, requiring significantly more data than practical or often possible. The source of this variability is seen below. Figure 24 illustrates time-space diagrams and travel time distributions on links 2 and 3 under the normal traffic state. When the traffic demand is under the capacity, the link travel time patterns can be defined by the traffic signal offset, vehicle speed, and the link distance. Also, when the front part of vehicle platoon reaches the downstream intersection (Figure 24 (c)) the system experiences more delay than when its rear part stops at the intersection (Figure 24 (a)).



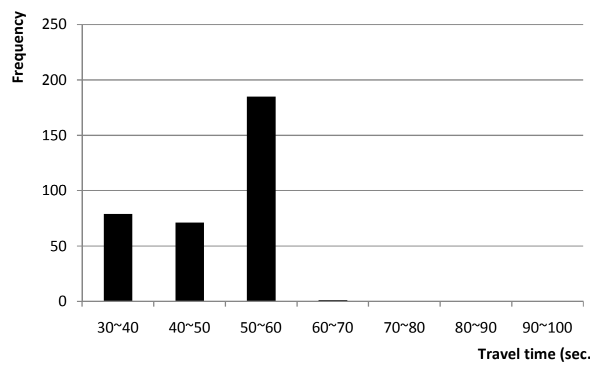
(a) Between location 1 and 2



(b) Travel time distribution at location 2



(c) Between location 1 and 3



(d) Travel time distribution at location 3

Figure 24: Time-space Diagram and Travel Time Patterns at Location 2 and 3

This potential variability makes it difficult to estimate and predict reliable travel times for implementing the ATIS in the signalized traffic network. This highlights a need to revisit the minimum sample size issue and the trade-off between reliable data and ignoring potentially meaningful information. Currently this additional effort is reserved for future research, with this study subsequently employing a minimum sample size 2 for each link to investigate the performance of the various ATIS models on signalized networks. In addition, while the GATIS-V2V model is a pure decentralized ATIS model, not supported by any infrastructure to collect traffic information, future research should take into account supplementary schemes to elicit the meaningful information at the low penetration ratios (i.e., limited sample sizes) for system updates.

6.3 Results and Analysis

6.3.1 Travel Time Comparison of Various GATIS-V2V Models

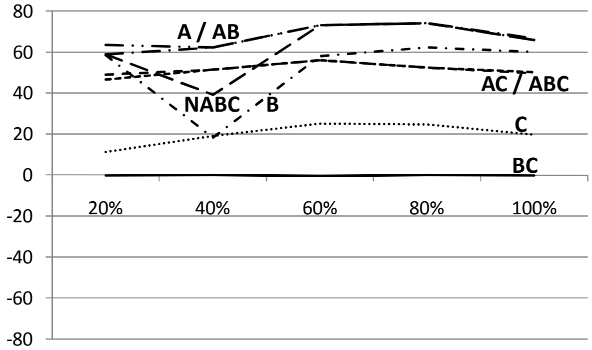
Figure 25 (a) shows the travel time savings patterns of participating and non-participating vehicles with eight ATIS cases at traffic demand 720vph, radio range of 625m, and for both incident locations. Focusing on the lower traffic incident case, comparing travel time savings patterns between the non-signalized and signalized traffic networks, the ATIS models implemented in the signalized network (Figure 25 (a)) tend to save more time than the non-signalized network (Figure 21 (c)). This is because the historical travel time of the lower route is consistently slightly longer than that of the upper route (Table 9), so some ATIS models (i.e., Cases A, B, AB, NABC) whose re-routings are not controlled by *I* factor (i.e., boundedly rational drivers' route selection rule) before the incident occurs seem to save more time than other ATIS models but this is partially due to the driver inertia to the upper route.

Interestingly, Figure 25 (a) shows that the travel time savings of Cases NABC and B at 40% penetration ratio deviate from the travel time saving patterns. This is because in five replicates out of the ten run the routes are updated to the lower route at 1260 seconds due to a longer travel time experienced at location 2. Since Case NABC does not have any restrictions to update the traffic incident compared to Case B, more vehicles change their route to the upper route, resulting in more travel time savings than Case B. Also, Case BC cannot update the route to the less congested route because it cannot meet the re-routing criteria like the non-signalized traffic network case. It is noted that a side experiment was run (results not shown) using 100 replicates for these scenarios and the deviation at 40% was removed. This indicates that the number of replications being used (i.e., 10) may not fully capture all trends due to the variability in the signalized network, however, computational recourses do not currently allow for additional replications over the entire experiment.

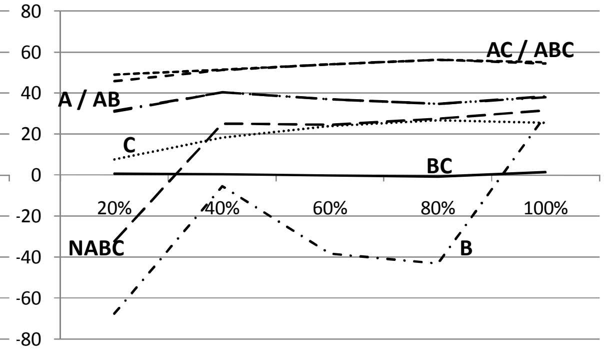
As seen in the non-signalized network, since Case C takes the realistic re-routing behavior into account, the re-routing due to small travel time improvements is prohibited. Also, Case C requires a participating vehicle to depart the incident link before travel time data reflecting the incident is broadcasted, leading to the less efficient system performance than those GATIS-V2V configurations that include the accident detection. Cases AC and ABC demonstrate consistent and robust system performance with Case AC providing slightly higher travel time savings than Case ABC due to the sample size limitation. The non-participating vehicles show the same travel time saving patterns as the participating vehicles (Figure 25 (c)).

The most significant difference in the re-routing patterns and travel time savings between the non-signalized and signalized traffic network is the effect of the historical link travel time reflected from the traffic signal parameters, resulting in more re-routing prior to the incident, simply due to the variability of travel time in the signalized traffic network. As a final point the signalized intersection, as with the non-signalized results, seems to show minimal improvement in participating vehicle time savings after the penetration ratio reaches 60%.

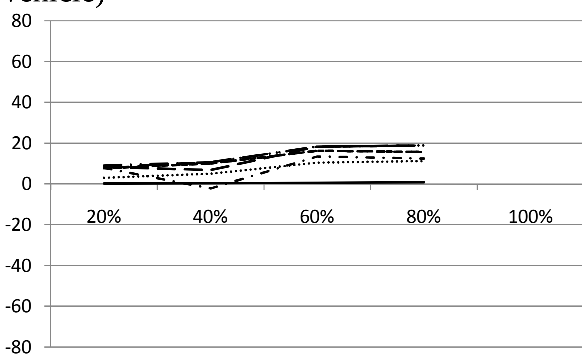
The effect of the historical travel time in the signalized traffic network can be highlighted by implementing the eight ATIS models with incident on the upper travel route. As can be seen in Figure 25 (b), while Cases C, BC, AC, and ABC show somewhat constant and stable system performance regardless of the incident location, Cases B and NABC indicate a dramatic change of saving travel time and Cases A and AB also creates noticeable difference in the system performance. Case B at 100% penetration ratio updates the incident and re-routes some vehicles. Thus, the location of the incident and the given historical travel time database (i.e., traffic signal parameter effect) can significantly impact model performance. The non-participating vehicles follow the same patterns of re-routing and travel time saving as the participating vehicles except that the travel time of small number of non-participating vehicles of Case B at 80% penetration ratio are significantly affected by vehicles re-routing to the upper route (Figure 25 (d)).



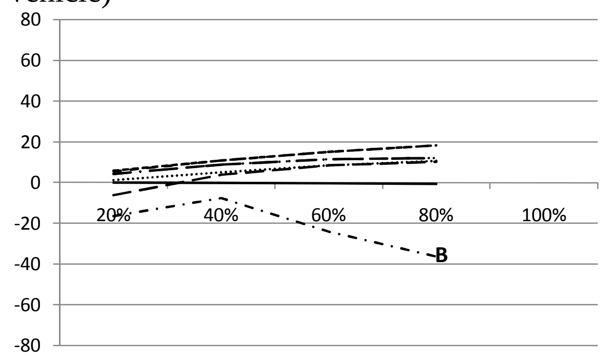
(a) Lower incident case (participating vehicle)



(b) Upper incident case (participating vehicle)



(c) Lower incident case (non-participating vehicle)



(d) Upper incident case (non-participating vehicle)

Figure 25: Average Travel Time Savings Comparison of Eight ATIS modes in Two Different Incident Cases

Note: X-axis is the penetration ratio and Y-axis is the average travel time savings

6.4 Summary

Implementation of ATIS model in the signalized traffic network is a significant challenge due to the significant variability of travel time resulting from the traffic signals. This travel time variability is reflected into the historical link travel time and the minimum sample size rules derived from the simple sample size equation or the heuristic method designed in this study. However, the minimum sample size likely should vary depending on the travel time variability and with links requiring travelled by significant number of participating vehicles. This results in significant trade-offs between data reliability and the ability to rapidly incorporate new data. This issue should be addressed by the future research.

The *I* factor (i.e., C-involved ATIS cases) is an important factor in avoiding unrealistic re-routing behaviors before the non-recurrent traffic state to secure reasonable system efficiency. The re-routing patterns are determined by *K* factor (i.e., A-involved ATIS cases) during the traffic incident. It is noted that the basic ATIS model (i.e., NABC case) performance is mainly influenced by traffic signal parameters (i.e., historical link travel time) and location of the non-recurrent traffic states, but the advanced models coupled with *K* and *I* factors are constant, consistent, and robust in their performance. Therefore, determination of the appropriate values of *K* and *I* factors is very important in improving the system performance. For example, a low *K* factor parameter value could be overly sensitive to the variability of the link travel time, leading to possible false congestion alerts while high value might not succeed in timely traffic incident detection and update, resulting in the same congestion as the no ITS-aided traffic network. In addition, intrinsic travel time variation generates the travel time discrepancy between routes, so prior to the significant travel time difference to the extent that the congestion alert system is activated is observed, the *I* factor has to be implemented to prevent the biased re-routing. Similar to the basic model, a low *I* factor parameter value would bring about likely unrealistic re-routing while high value would not allow vehicle to take more efficient routes. The following section will consider the sensitively of travel time to the *K* and *I* parameters.

6.5 Sensitivity Analysis of *K* and *I* Factors (Monte Carlo Simulation Method)

The three complementary functions in the advanced GATIS-V2V model provide a more realistic model of driver (i.e., driver indifference factor), quickly detect and disseminate incident information (i.e., congestion detection factor), and utilizing reliable link travel time in updating the travel time and routes (i.e., minimum sample size). Simulation outputs provided above for the signalized traffic network have been obtained with the fixed parameter values of K = 3 (i.e., travel time of a vehicle on a link must exceed the historical travel time by a fact of three to trigger an accident warning message) and I = 20% (i.e., the travel time of an alternate route must be provided at least 20% savings before a participating vehicle change paths). Obviously, these parameter values should be fine-tuned depending on the various traffic-related factors such as traffic flow, penetration ratio, traffic signal timing parameters, etc. Thus, this research conducts the sensitivity analysis to obtain the more insights into the relationship between the K and I parameter values and system performance using Monte Carlo simulation.

6.5.1 Experimental Design

Sensitivity analysis is conducted using the same traffic network in Figure 22, considering only the lower route incident case. In practice, the time-dependent minimum sample size option could be implemented; however, as discussed earlier this section utilizes one set of minimum sample sizes (i.e., minimum sample size 2 for all links) instead of that calculated from the historical travel time. Also, the congestion alert function has priority over other functions, thus, when congestion information is received from a neighboring participating vehicle, even before the system update time interval, the travel time database update and best route calculation processes are executed without taking into account the minimum sample size option.

The Monte Carlo simulation method uses the randomly selected input parameters to observe the effect of the sensitivity parameter in the iterative procedure until the process meets the stopping criteria. Table 10 provides the parameter values considered in the sensitivity analysis.

Table 10: Used Parameters and Values for Sensitivity Analysis

<table>
<tr><th colspan="2">Parameter</th><th>Value</th></tr>
<tr><td rowspan="2">Sensitivity parameter (36 cases)</td><td>K factor</td><td>0, 1, 2, 3, 4, 5</td></tr>
<tr><td>I factor</td><td>0%, 10%, 20%, 30%, 40%, 50%</td></tr>
<tr><td rowspan="3">Random parameter</td><td>Flow rate</td><td>Between 300vph and 720vph</td></tr>
<tr><td>Radio range</td><td>Between 250m and 625m</td></tr>
<tr><td>Penetration ratio</td><td>Between 0% and 100%</td></tr>
</table>

Figure 26 depicts sensitivity analysis procedure. For 36 sets of sensitivity parameters (*K* and *I* factors) three input parameters (F: flow rate, R: radio range, P: penetration ratio) are randomly chosen within the given range, respectively to run the advanced GATIS-V2V model (i.e., ABC model). When the error between sample mean of travel time savings of re-routing participating vehicles and the population mean is under the user-defined marginal error (i.e., 20 seconds) at the 95% confidence rate, the Monte Carlo process for one set of sensitivity parameter is stopped. Although the error between the sample and the true population should be calculated with the population standard deviation, when the sample size is over 30 (k > 30), the sample standard deviation (s_{ij}) can substitute the population standard deviation.

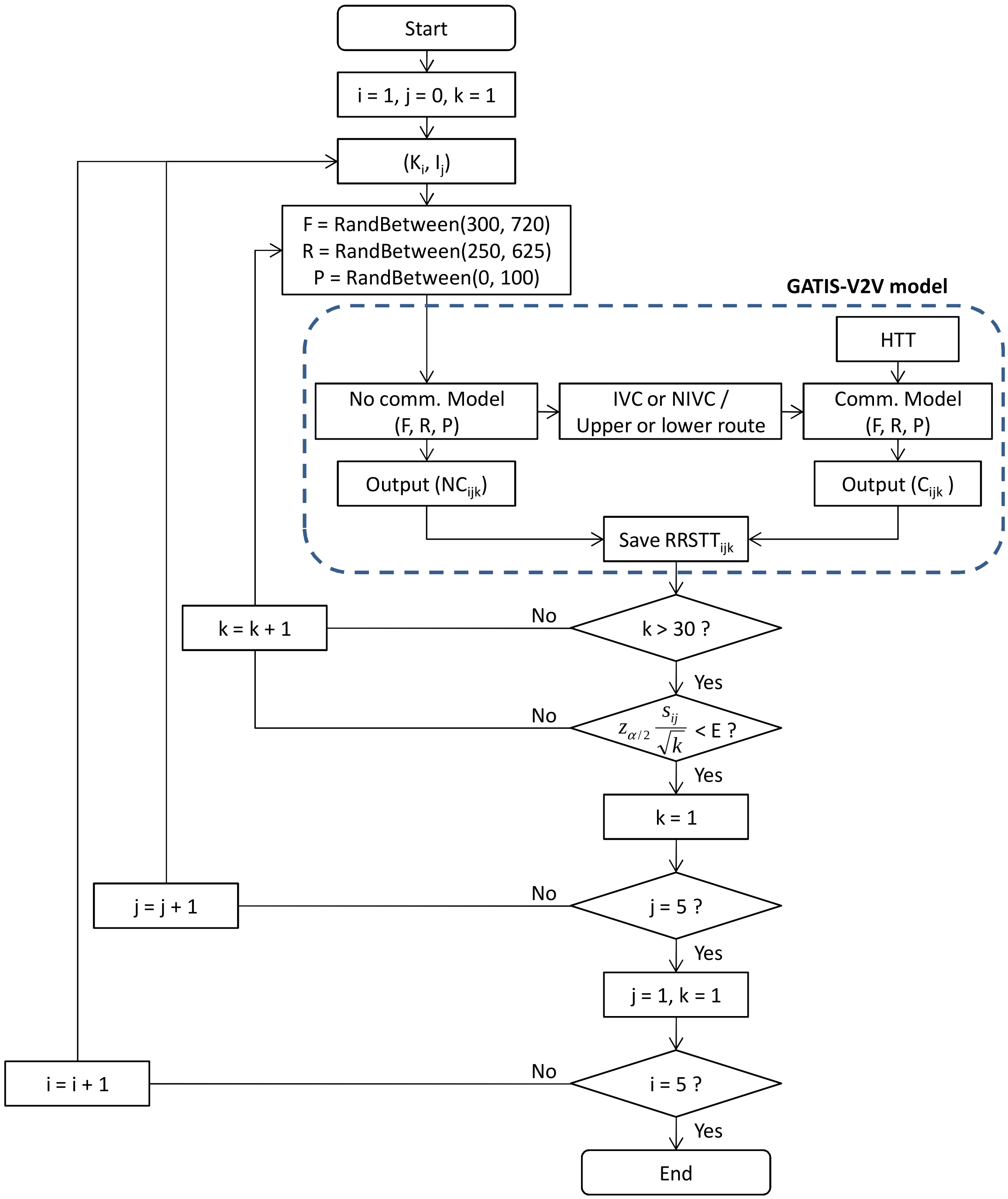


Figure 26: Monte Carlo Simulation Flow Chart for Sensitivity Analysis

6.5.2 Results and Analysis

The *I* factor is the route-based re-routing function responding when the current route traffic time is greater than the guided one by the *I* factor parameter ratio of the current route travel time. The *K* factor and the minimum sample size options can be defined as the link-based re-routing functions reacting to the comparatively long link travel time to the historical link travel time and sufficient number of travel time records satisfying the minimum sample size for each link. The sensitivity analysis results are described as follows with Table 11, Table 12, Table 13, and Table 14.

A) *K* factor = 0 (i.e., no congestion alert function) and *I* factor

- When *I* factor is 0%, a small travel time difference triggers re-routings. Most re-routings prior to the incident is due to the lower route historical travel time being higher than the upper route (Table 9). In addition, during the effective incident time period the system guides vehicles to the upper route. In rare instances it is possible for a vehicle to change from the upper to lower route as under normal driving conditions the lower route will occasionally show minimal potential improvement due to system variability (Table 14).
- As *I* factor value increases, the less re-routings occur as the re-routing rule becomes stricter (Table 13 (a)), resulting in less average travel time savings (Table 14). That is, more route travel time discrepancy is required to change routes. Notice, nearly all of the re-routing occurs as a result of differences with the historical data. For the given incident one car is released every 90 seconds. Thus, two vehicle travel times are recorded each three minute bin. The historical

data will only be update with actual travel times when both of these vehicles are instrumented, which is a relatively rare event, particularly at the lower penetration rates.

B) *K* factor = 1 (i.e., actual link travel time > historical link travel time → congestion alert issue)

- Every time the experienced travel time is longer than the historical travel time, vehicles issue and disseminate the traffic congestion message possibly for all links and informed vehicles instantly update their route, without considering the sample size condition. Every moment the route is updated the current route and the alternative route might contain the traffic incident message (i.e., unattainable travel time) and then the *I* factor should be employed for the final route decision.
- As with the *K* = 0 case, as the *I* factor value increases less re-routing occurs and with some vehicles changing their routes from the upper to the lower path (Table 13). Accordingly, the travel time savings decrease with increasing *I* (Table 14). Finally, it is noted that the high system performance variability (i.e., high fluctuating travel times) introduced by *K* = 1 results in a significantly higher number of runs to meet the stopping criteria than for other values of *K* (Table 12).

C) *K* factor = 2, 3, 4 and 5

- When *I* factor is 0%, re-routing vehicles consist of vehicles re-routing before the incident and during the incident, but when *I* factor is implemented, most vehicle re-routings are triggered by the traffic congestion messages during the effective traffic incident time period. Therefore, more vehicles at *I* factor = 0% are re-routed with an averaged saved time greater than any other *I* factor cases (Table 13 (a) and Table 14).

- Since the high accident message travel time is updated in the historical database immediately, the number of vehicle re-routings and average travel time savings become relatively independent of *I* when *I* = 20%, 30%, 40%, and 50%, with the difference within the data variability (Table 13 (a) and Table 14).
- In addition, different *K* factor values do not significantly affect the number of vehicle re-routings or average travel time savings. This is likely a direct result of the experimental design. The historical link travel time of the incident link (i.e., Link 5) is 32 seconds, thus and *K* = 5 case (i.e., last incident update case) has just 96-second delay in issuing the congestion message compared to *K* = 2 case (i.e., fastest incident update case). This time difference accounts for the seven participating vehicles at the 100% penetration ratio and fewer at lower participation ratios, which is not sufficient to generate the significant difference in the re-routing number and travel time savings (Table 13 (a) and Table 14). However, if the historical link travel time of interest is significantly long relative to the additional delay due to the incident, the system performance could differ from this experiment.

In conclusion, from the aspect of the system efficiency and reality, the timely update of the traffic incident and the realistic route choice behavior are very important to system performance. A reasonable *K* factor value concerning the system efficiency is likely in the range of 2 or 3, as on links with travel times longer that those tested a value of 4 or 5 might impose a significant delay on vehicles. Also, future research should consider the possibility of *K* being a function of the mean and standard deviation of the historical link travel time, making the accident identification more robust to different facility and area types. Also, result would seem to indicate that a reasonable *I* factor would also range from 20% to 30% as an *I* = 10% likely fails to realistically reflect drivers inherent tendency to stay on their current routes.

Table 11: Travel Time Savings Error when the Stopping Rule is Satisfied

		I factor					
		0%	10%	20%	30%	40%	50%
K factor	0	14.4	15.5	3.9	3.2	2.1	0.4
	1	19.9	20.0	20.0	20.0	20.4	20.0
	2	10.9	19.8	19.8	19.7	19.9	20.0
	3	12.0	19.7	20.0	20.0	19.9	19.7
	4	19.7	19.9	20.0	19.9	20.0	19.7
	5	17.6	19.7	20.0	19.9	19.8	19.6

Table 12: Number of Simulation Runs Required until Conversion to the Criteria

		I factor					
		0%	10%	20%	30%	40%	50%
K factor	0	31.0	31.0	31.0	31.0	31.0	31.0
	1	56.0	85.0	132.0	146.0	261.0	326.0
	2	31.0	108.0	33.0	68.0	113.0	104.0
	3	31.0	77.0	108.0	85.0	75.0	43.0
	4	46.0	65.0	60.0	67.0	102.0	93.0
	5	31.0	47.0	85.0	82.0	69.0	67.0

Table 13: Re-routing Participating Vehicle Information

(a) Average number of re-routing participating vehicles							
		I factor					
		0%	10%	20%	30%	40%	50%
K factor	0	81.4	24.7	15.0	15.1	7.2	2.4
	1	74.6	62.4	50.0	37.7	24.2	11.8
	2	82.5	45.1	53.1	50.6	47.0	53.8
	3	88.4	55.4	45.9	57.6	43.6	68.5
	4	63.4	67.0	49.7	51.7	48.1	48.8
	5	76.3	63.9	53.9	48.5	55.9	64.6
(b) Average number of re-routing participating vehicles from upper to lower route							
		I factor					
		0%	10%	20%	30%	40%	50%
K factor	0	0.5	0.0	0.0	0.0	0.0	0.0
	1	20.6	17.1	13.0	7.5	3.6	1.5
	2	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.2	0.0	0.0	0.0	0.0	0.0
	4	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.0	0.0	0.0	0.0	0.0	0.0
(c) Average number of re-routing participating vehicles from lower to upper route							
		I factor					
		0%	10%	20%	30%	40%	50%
K factor	0	80.9	24.7	15.0	15.1	7.2	2.4
	1	54.0	45.2	37.0	30.2	20.6	10.4
	2	82.5	45.1	53.1	50.6	47.0	53.8
	3	88.1	55.4	45.9	57.6	43.6	68.5
	4	63.4	67.0	49.7	51.7	48.1	48.8
	5	76.3	63.9	53.9	48.5	55.9	64.6

Table 14: Average Travel Time Savings of Re-routing Participating Vehicle

		I factor					
		0%	10%	20%	30%	40%	50%
K factor	0	198.7	11.8	2.6	3.3	0.6	0.2
	1	218.1	204.0	202.0	187.2	180.4	146.1
	2	209.2	186.6	181.5	190.3	179.2	191.5
	3	203.2	190.5	192.7	183.5	185.2	187.8
	4	213.1	200.0	181.3	204.9	176.9	187.2
	5	212.6	168.0	165.7	185.0	174.7	199.6

6.5.3 Summary

This section explored the sensitivity of the travel time savings of the re-routing vehicles to complementary functions *K* and *I* using Monte Carlo simulation method. The findings from the sensitivity analysis are summarized below:

At *K* factor = 0, the re-routing pattern are dependent on the *I* factor, As the *I* factor value increases less re-routings and less travel time savings are realized. Also, at *K* factor = 1, traffic congestion messages could be issued on any links and the routes updated with the congestion messages could be the upper, lower or both. As with the *K* factor = 0 case, the *I* factor controls the number of re-routing and travel time saving patterns. For the different *K* factors greater than 1 vehicle re-routings are triggered by updating the traffic incident and satisfying the *I* factor values. Interestingly, *I* factor = 0% case re-routes more vehicles and saves more time due to no restriction on the route travel time difference.

In selecting an *I* value it is recognized that the travel time variability due to the traffic signal effect can easily result in 10% or greater fluctuations in travel under the normal traffic states. On the other hand, normal operations tend not to result in average travel times differing by 40% or 50% of the historical travel time, without any unusual traffic states that will be updated with the congestion alert function. Therefore, triggering vehicle re-routing at 20% or 30% relative travel time saving from the current route seems to be reasonable. Regarding the *K* factor a low value might issue too many false alarms of the traffic congestion due to expected travel time variability on a signalized traffic network. A high *K* factor value will delay the non-recurrent traffic state update. Hence, the sensitivity analysis of *K* and *I* factors to the advanced GATIS model performance suggests the utilization of 2 or 3 for the *K* factor and 20% or 30% for *I* factor.

CHAPTER 7 EVALUATION OF GATIS-V2V MODEL IN SIGNALIZED URBAN GRID NETWORK

7.1 Introduction

Chapters 4, 5, and 6 demonstrated that the GATIS-V2V model is efficient in saving travel time, particularly, the advanced model produced more consistent and robust system performance in the simple signalized and non-signalized traffic network. Chapter 7 evaluates the performance of the advanced GATIS-V2V model in the typical urban grid network after verifying three system modules.

This chapter is distinguished from other studies on ITS applications using vehicle communication in that the advanced GATIS-V2V is a broader ITS application framework using vehicle communication. In other words, most other studies consider partial topics such as vehicle communication only, re-routing application without database management strategy, use of travel time with no link separation, no system-enhancing functions, and so forth.

7.2 Experimental Design

The advanced GATIS-V2V model incorporates the developed processes described in Chapter 3, such as the operational and introductory data pre-processes, the main processes, and the three complementary functions. The *K* and *I* factors are set to 3 and 20% for AAID algorithm and drivers' route choice rule, respectively, based on the sensitivity analysis results. As discussed in Section 6.2, this chapter also employs 2 travel time records for one system update time interval as the minimum sample size for each link. Travel times categorized into five types on one link are updated, estimated, and utilized to search for the best route from the current location to the final destination either instantly when the traffic congestion messages are received or at the pre-determined system update time interval (i.e., 3-minute in this study). In practice, this travel time separation for one link makes it more difficult to reliably estimate and predict the travel time in the real world and the roadside activities such as driveway access and parking would increase the travel time variability on the link, resulting in an increasing sample size requirement.

In addition, three underlying system parameters are set to 300vph and 514vph for traffic flow, 250m, 375m, and 500m for communication radio range, and 10% to 50% in 10% increment for penetration ratio. Data dissemination speed, accuracy of the travel time estimates, and number of re-routing vehicles are utilized for the system verification. Average travel time savings of participating, non-participating, and (instant) re-routing vehicles are exploited as metrics to evaluate the system performance. Interestingly, all routes are instantly updated because while the scheduled database and route updates cannot generate 20% travel time difference between the current and the system-guided routes under the normal traffic condition, participating vehicles under the non-recurrent traffic state perform their update process at the moment traffic congestion messages are received.

Figure 27 and Table 15 provide the 6X6 urban grid traffic network and relevant information. An Eastbound traffic incident (the dark star in Figure 27) is located in the center of the network. The incident occurs from 1000sec to 2000sec, with a vehicle release every 90sec.

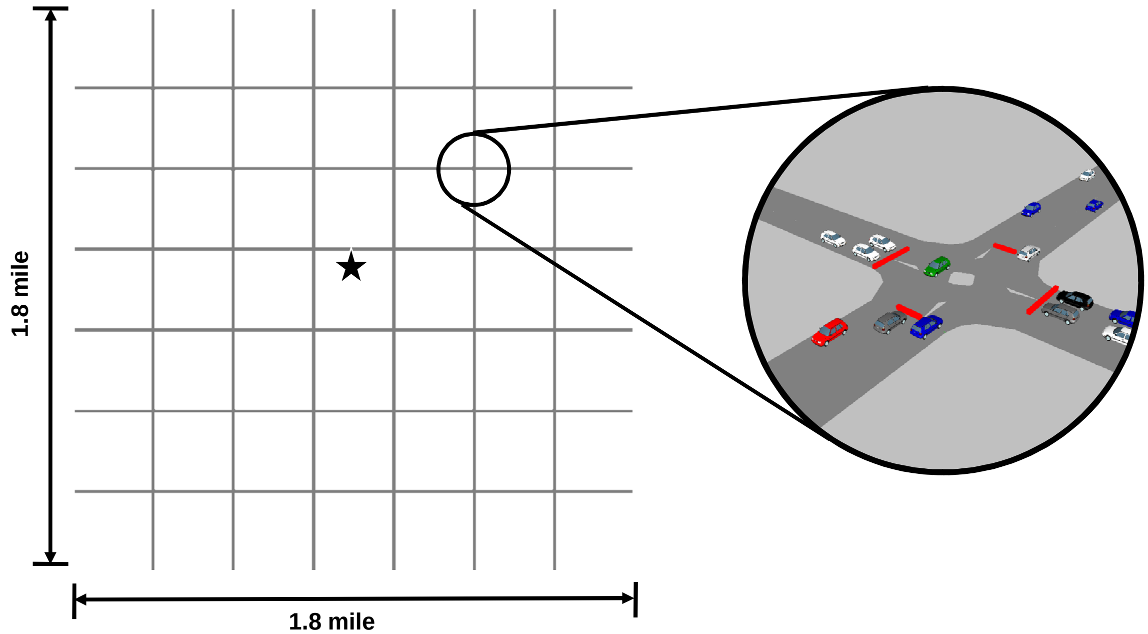


Figure 27: Artificial 6X6 Typical Urban Traffic Network

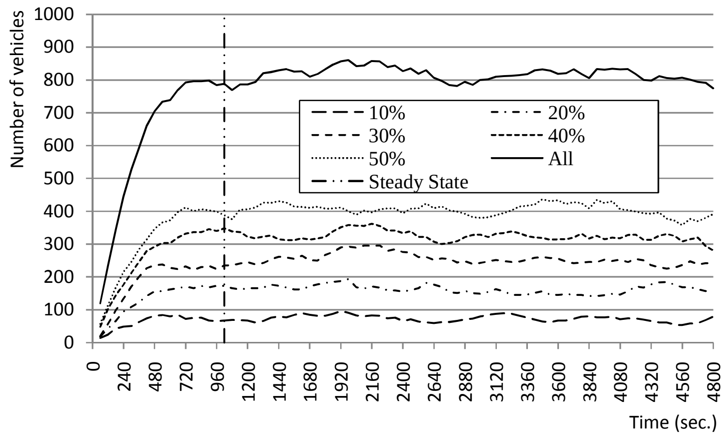
Note: zoomed-in circle = a typical intersection controlled by the traffic signal

Table 15: 6X6 Traffic Network Information

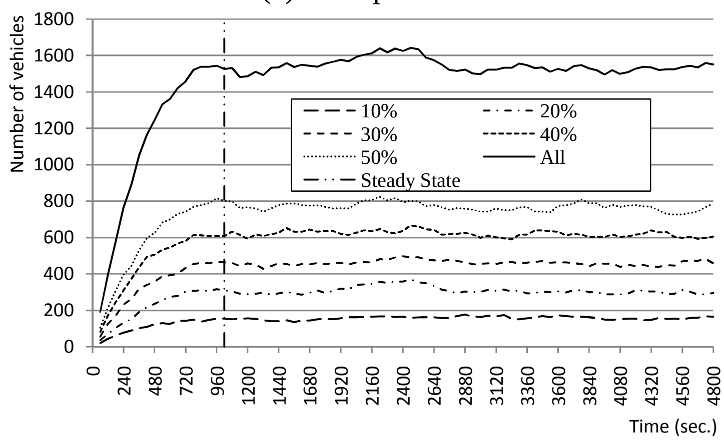
Category	Item	Value	Notes
Geometry	1 lane with left-turn lane		
	Number of Links	720	Five separate links for one link
	Left-turn distance	183m	600ft.
	Link distance	382m	1250ft.
Traffic signal	Cycle length	120sec	
	Phase	EBL & WBL: 11sec	Split phase
		EBT & WBT: 41sec	
		SBL & NBL: 11sec	
		SBT & NBT: 41sec	
	Offset	0sec	
Traffic operation	Vehicle generation	300vph and 514vph	12sec and 7sec constant headway
	Turning ratio	Through: 70%	
		Left: 15%	
		Right: 15%	
	Desired speed	48kph	30mph
	Traffic incident	1000 sec to 2000 sec	One vehicle release at 90 sec headway

7.3 GATIS-V2V Model Verification in the Large Network

Prior to evaluation of the advanced GATIS-V2V model in the large signalized traffic network, the behavior of three fundamental modules has been verified so as to ensure that difference of the simulation output results from the varying system parameters. All verification processes have been conducted after the steady-state traffic condition is attained. Figure 28 shows the number of vehicles and participating vehicles in the network every second for 300vph and 514vph cases and the steady-state traffic condition is attained approximately at 1000sec for both traffic flow cases.



(a) 300vph case



(b) 514vph case

Figure 28: Traffic Volume Patterns for All Vehicles and Participating Vehicles

7.3.1 Vehicle Communication

A) <u>Vehicle communication group formation process</u>

Figure 29 shows an example of communication group formation process with 300vph flow rate, 250m radio range, and 10% penetration ratio case under the ideal communication environment (i.e., no signal interference and no data loss in communication). Twenty-two communication groups have been formed at this moment and the dynamic establishment and breaking of communication links will dissipate the traffic information throughout the network.

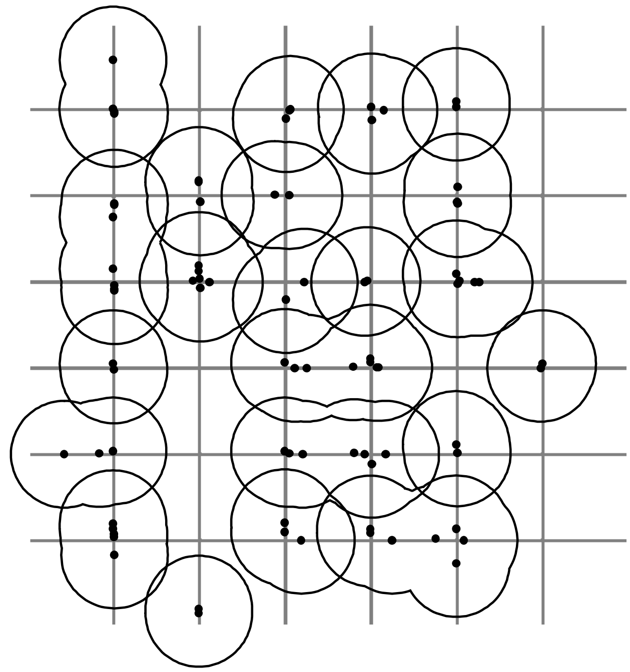
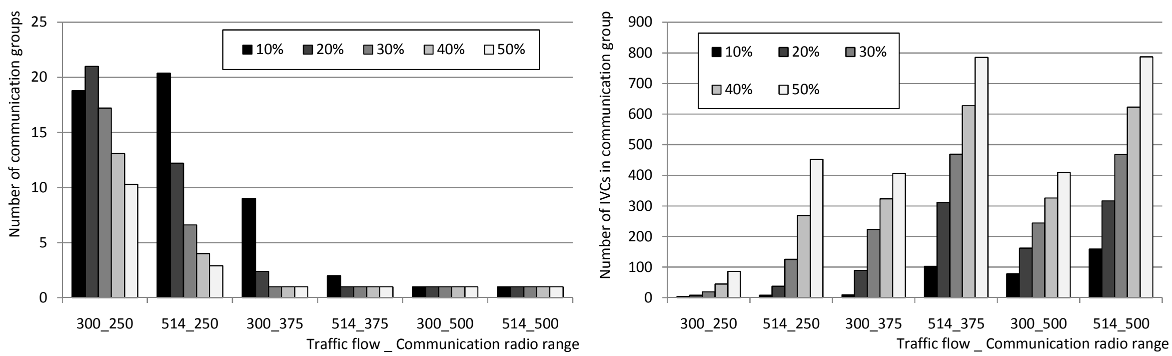


Figure 29: Example of Communication Group Formation

As expected, Figure 30 depicts that high flow rate, wider radio range, and high penetration ratio have fewer communication groups and more participating vehicles per communication group. Interestingly, the number of communication groups in (300, 250, 10) case ((flow rate, communication radio range, penetration ratio) represents a specific case hereafter) is smaller than that of (300, 250, 20) case because the traffic flow, radio range, and penetration ratio in the former case are limited for communication formation. On the other hand, from (300, 250, 20) case the communication group formation patterns show the intuitive effect of the three key system parameters.

While communication group numbers seem to be dominated by the penetration ratio at the short radio range (250m), the intermediate radio range (375m) is long enough to generate one communication group containing all participating vehicles available in the network, excluding a few low penetration ratio cases like (300, 375, 10), (300, 375, 20) and (514, 375, 10). Taking the link distance (382m) into account, this result seems very reasonable. For instance, as the number of communication groups decrease, the average number of participating vehicles in one communication group increases. Therefore, an update of link travel time can be disseminated simultaneously to all participating vehicles in the network.



(a) Average number of communication groups

(b) Average number of participating vehicles in one communication group

Figure 30: Output of Vehicle Communication Group Formation

B) <u>Data dissemination process</u>

The elapsed time required for the travel time of the bottom left vertical or horizontal link to reach the center of the network (indicated by the square box) through multi-hop communications has been observed for the verification of data dissemination process after the steady-state traffic condition is attained (Figure 31).

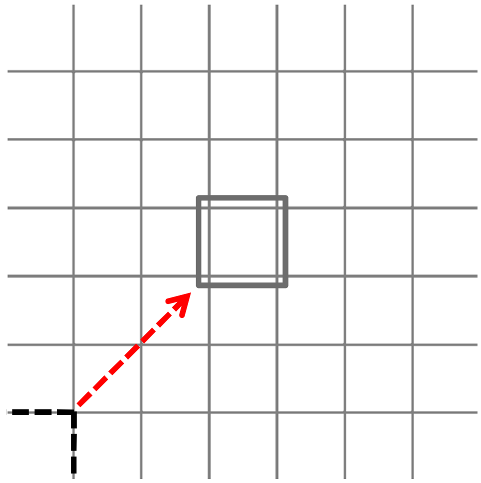


Figure 31: Data Dissemination Speed Measuring Method

Figure 32 reveals that more communication-favorable cases (i.e., high flow rate, wider radio range, and higher penetration ratio) facilitate fast data dissemination with the short elapsed time.

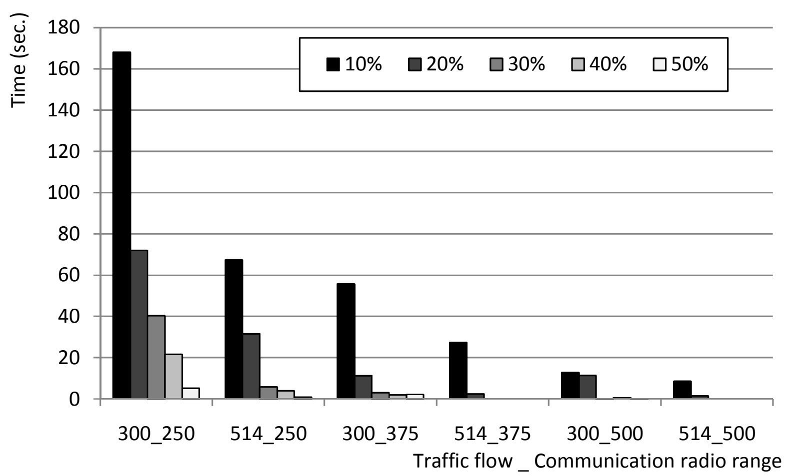


Figure 32: Data Dissemination Speed

In addition, this research investigates how many links are covered (i.e., a vehicle passes and sends a travel time) by at least one participating vehicle every system update time interval. This metric is directly related to the traffic demand and number of existing participating vehicles, but less to the radio range as one system update time interval (i.e., 3min) is a sufficiently long time that any participating vehicles can pass at least one link and share that travel time network-wide neighboring vehicles due to repeated and frequent establishment and breaking of communication links. Figure 33 indicates that a fairly consistent number of links is covered by individual participating vehicles for each traffic flow case and associated penetration ratio case, except at the lower penetration ratio cases because as the penetration ratio decreases the radio range is more considerable for both traffic flows in forming the communication group.

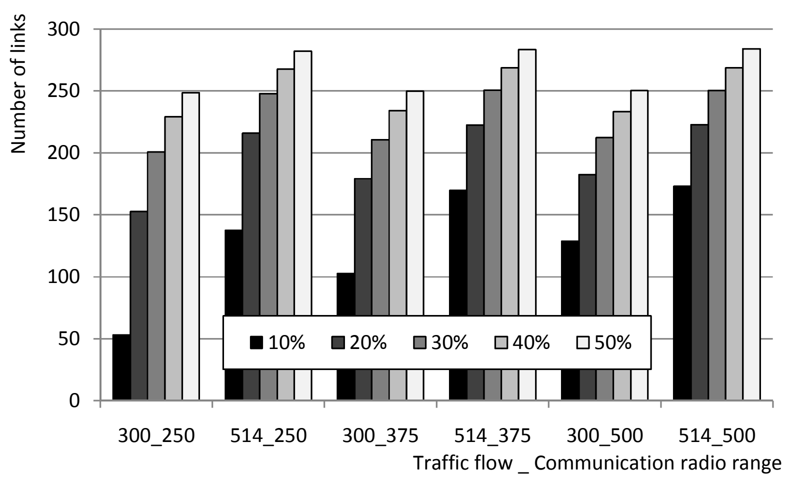


Figure 33: Number of Links Covered by Communication Radio Range

7.3.2 Database Management Strategy

When responding to an incident vehicle re-routings, database, and route update processes occur at the moment participating vehicles receive a traffic congestion message. In addition, the database management strategy has to update and record the traffic congestion message in the corresponding cell of its STM. The communication module handles messaging from participating vehicles with screening rules (no duplicated vehicle ID and relatively up-to-date data only). When participating vehicles finally pass a congestion area, their traffic congestion messages should be updated with the actual link travel time. Thus, the database management strategy should be able to find the exact location of the associated congestion message in the corresponding cell of the STM and update it with the actual travel time. Also, this update process should be implemented in other participating vehicles having the associated congestion messages through vehicle communication. Otherwise, more vehicles could unnecessarily re-route adversely effecting system performance.

In addition, as stated in Section 3.2.1 B), since one link can be virtually considered as five different links due to travel time patterns from the upstream and downstream intersections, when a participating vehicle creates the traffic congestion message on one of five virtual links, the database management strategy should issue more congestion messages on the remaining virtual links to help other vehicles avoid congested conditions on the same physical roadway segment. For example, if a congestion message is issued on the through (upstream) → through (downstream) movement on one link, the left turn (upstream) → right turn (downstream) movement should be assigned a congestion message as well. Taking into account all of these functions, the on-board database management strategy can be verified with the number of re-routing vehicles under varying system parameter scenarios.

Figure 34 indicates the number of re-routing vehicles for different traffic flow, radio range, and penetration ratio. As expected, as the parameter becomes more communication-friendly, more vehicles re-routes, with the exception of the radio range. This is because participating vehicles with the radio range 250m require more time to receive and update the congestion message than other participating vehicles with the wider radio range. Thus, the similar numbers of participating vehicles can update their routes to the less congested one, only with some delay in the actual re-routing.

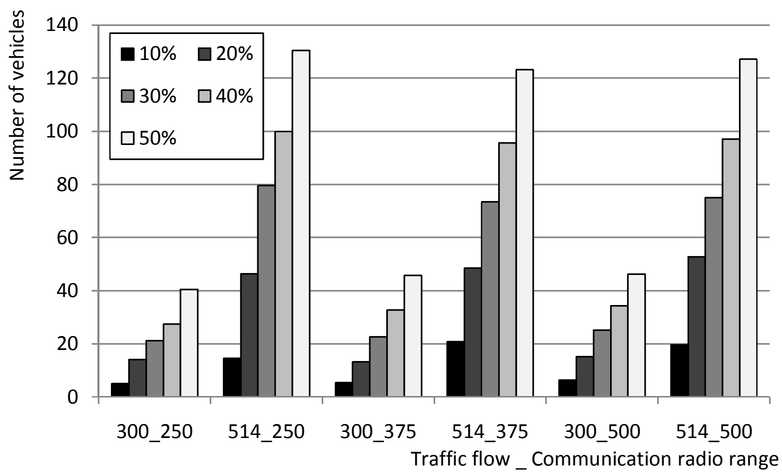
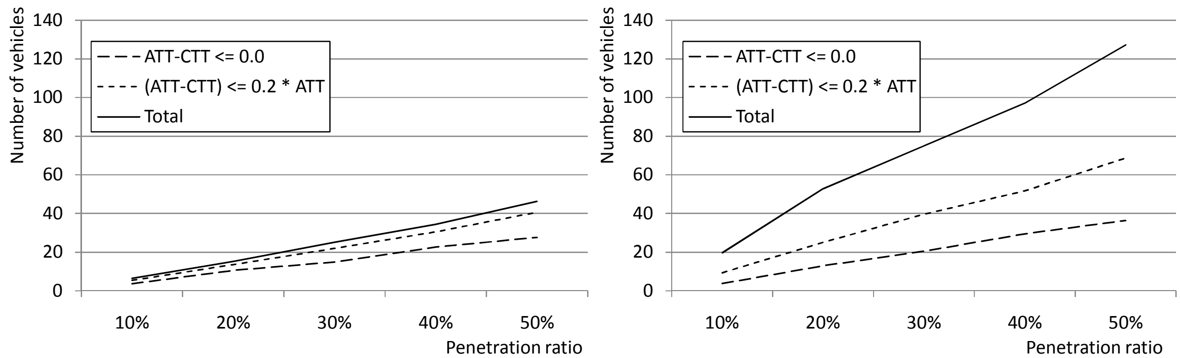


Figure 34: Number of (Instant) Re-routing Participating Vehicles

7.3.3 Dynamic Route Guidance System

As stated earlier, efficient implementation of an ATIS using travel time in the signalized urban grid network is a significant challenge due to the large travel time variation. Therefore, the estimated travel time of the system-guided route obtained from the instant database and route update processes could be significantly different from the actually experienced travel time. Bearing this in mind, this research investigates the accuracy of the cognitive travel time (i.e., initial historical travel time) of the system-guided route compared to the actual travel time as part of the DRGS module verification.

Additionally, this research assumes that drivers will not negatively perceive performance if the actual travel time is shorter than the informed cognitive one and also some drivers can endure somewhat prolonged travel time over the informed one (defined as a patient driver group). Figure 35 shows the number of re-routing vehicles whose actual travel time is shorter than, or equal to, the cognitive travel time and also longer by up to 20% with the radio range 500m cases. It is seen that approximately 60% of re-routing vehicles in the 300vph flow rate case have an actual travel time less than or same as the cognitive one, and when considering prolonged actual travel time up to 20%, more than 80% of re-routing vehicles fall into this group (Figure 35 (a)). For the 514vph cases more than 70% of re-routing vehicles experienced longer travel time than the cognitive one and slightly over 50% of re-routing vehicles have an actual travel time of up to 20% over the cognitive (Figure 35 (b)). A close investigation of the longer travel time of re-routing participating vehicles than their cognitive travel time in the higher traffic demand case reveals that a significant portion of participating vehicles tend to select a few specific links to detour around the congested link, resulting in issuing congestion messages on other links adjacent to the incident link. For DRGS verification purpose, it is expected that the number of re-routing vehicles is dependent on traffic flow and penetration ratio, but the radio range is not critical factor affecting the accuracy of the estimated travel time. However, it should be noted that most re-routing vehicles saved their travel times for both traffic demand cases as can be seen in Figure 38.



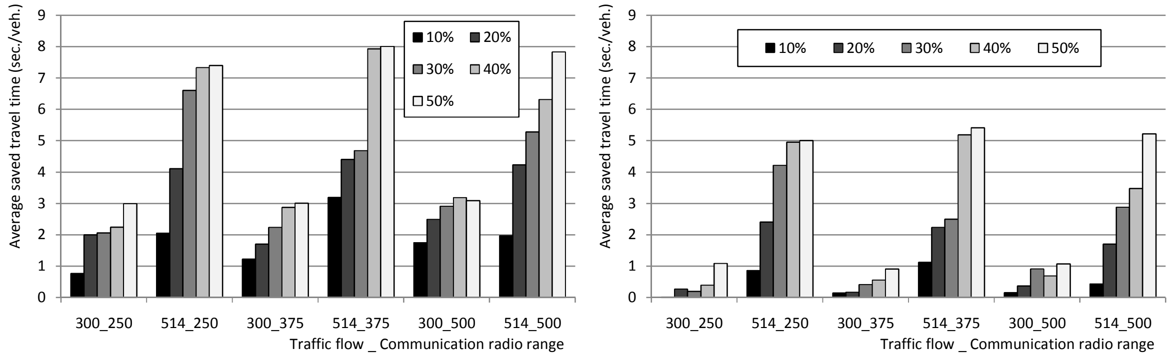
(a) 300vph and 500m case (b) 514vph and 500m case

Figure 35: Actual and Historical Travel Time Difference of Re-routing Vehicles

Note: ATT = actual travel time, CTT = cognitive travel time (i.e., historical travel time)

7.4 System Performance Evaluation

The advanced GATIS-V2V model operated by three key modules with three complementary functions is evaluated with respect to the average travel time savings of all participating and non-participating vehicles as well as all (instant) re-routing participating vehicles, followed by the temporal and spatial analysis of vehicle re-routing patterns. Figure 36 indicates that higher flow rates and penetration ratios result in a higher average travel time savings for participating and non-participating vehicles. Travel time savings are generated from the traffic incident-involved re-routing of participating vehicles. This figure confirms that the communication radio range is not a significant parameter in the system-performance.



(a) Average travel time savings of all participating vehicles

(b) Average travel time savings of all non-participating vehicles

Figure 36: Average Travel Time Savings of Participating and Non-participating Vehicles

Focusing on (instant) re-routing vehicles contributing to saving travel time, Figure 37 shows that even though number of (instant) re-routing vehicles in 300vph case is much less than that of 514vph case (Figure 34) the former case seems to save more time per instantly re-routed vehicle than the latter case. The following investigation addresses this issue using the (300, 375, 30-40-50) and (500, 375, 30-40-50) cases by way of example.

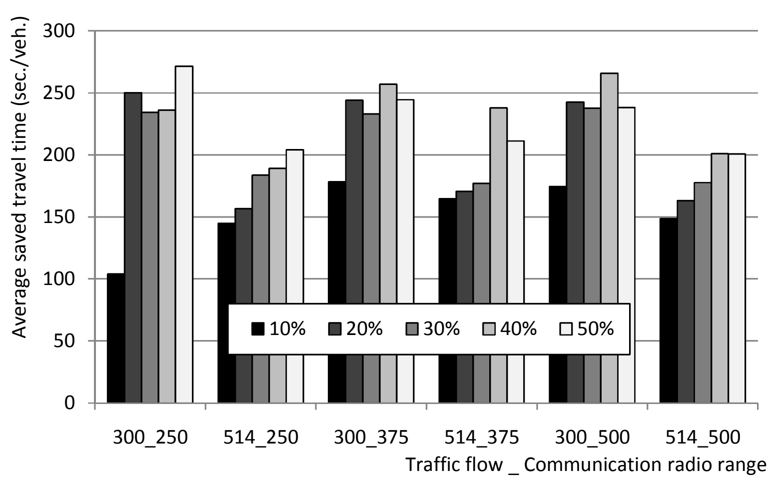
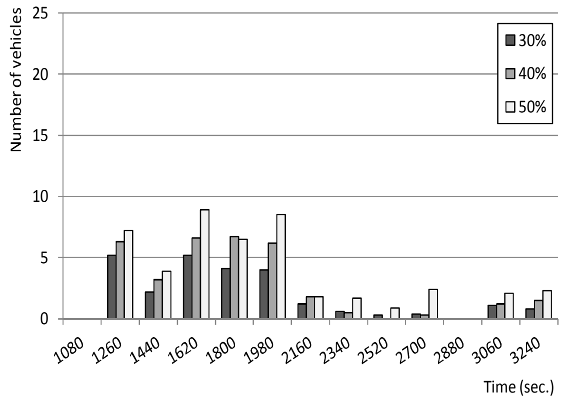


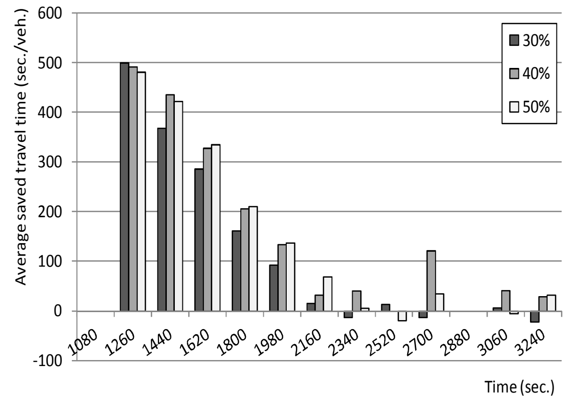
Figure 37: Average Travel Time Savings of (Instant) Re-routing Participating Vehicles

7.4.1 Temporal Analysis

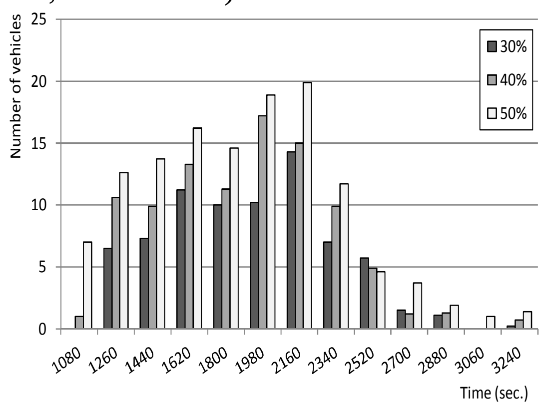
Figure 38 depicts the temporal pattern of re-routing vehicles and average travel time savings. The 500m radio range case data at penetration rations of 30%, 40%, and 50% is selected for comparison. Figure 38 confirms that travel time savings are greater for vehicles that re-route relatively soon after the incident and that the number of re-routing vehicles is relatively densely distributed between 1200sec to 2500sec as a result of traffic congestion messages during the effective traffic incident time period (Figure 38 (a) and (c)). Vehicle re-routing effect on the system performance with the low traffic flow case (Figure 38 (b)) is almost negligible from 2160sec because the traffic state quickly returns to the normal traffic condition after the traffic incident is resolved. For the high flow rate case a significant portion of re-routing vehicles after the traffic incident is resolved are triggered by traffic congestion messages issued on other links adjacent to the incident link as an aftermath of the traffic incident and by previous traffic congestion messages that have not yet expired (Figure 38 (d)). The travel time saving of these incidents is lower than that of vehicles re-routed around the primary incident. Consequently, the average travel time savings of re-routed vehicles in the higher flow case is lower. Also, a close investigation shows that since relatively more participating vehicles are distributed around less efficient time period with (300, 500, 50) case, travel time savings of (300, 500, 50) case in Figure 37 is lower than that of (300, 500, 40).



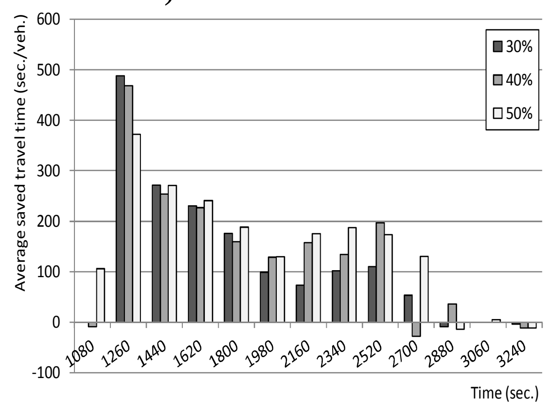
(a) Number of re-routing vehicles (300, 500, 30 – 40 – 50) case



(b) Average travel time savings (300, 500, 30 – 40 – 50) case



(c) Number of re-routing vehicles (514, 500, 30 – 40 – 50) case



(d) Average travel time savings (514, 500, 30 – 40 – 50) case

Figure 38: Temporal Analysis of Vehicle Re-routing and Average Travel Time Savings

7.4.2 Spatial Analysis

Besides the temporal analysis of re-routing patterns and travel time savings of participating vehicles, this research also performed a spatial analysis of re-routing vehicles to investigate the spatial relationship between the traffic incident location and vehicle re-routing location and travel time savings. Figure 39 illustrates the location of vehicles when the last re-routing occurs due to the traffic incident location.

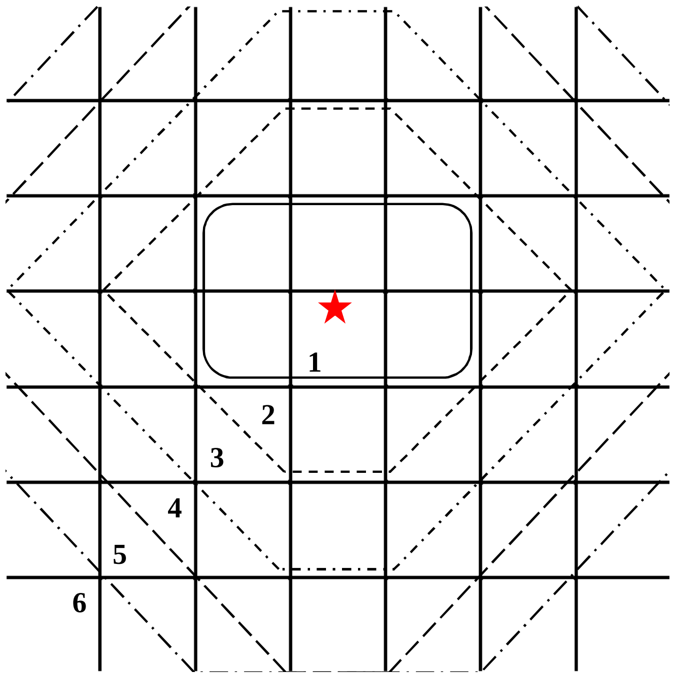
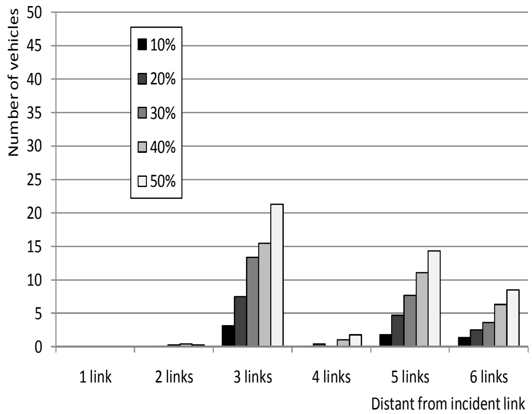
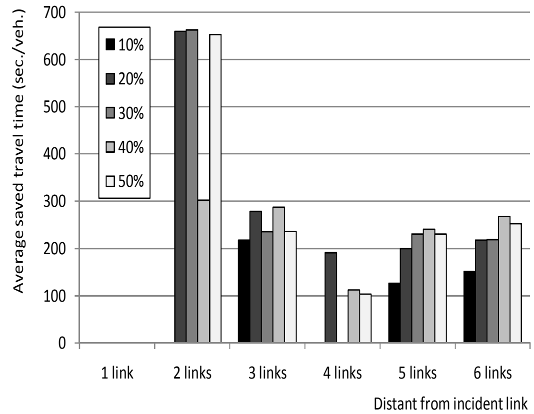


Figure 39: Link Distance from the Incident Link
Note: # = zone number of which links are distant from the incident link by # links

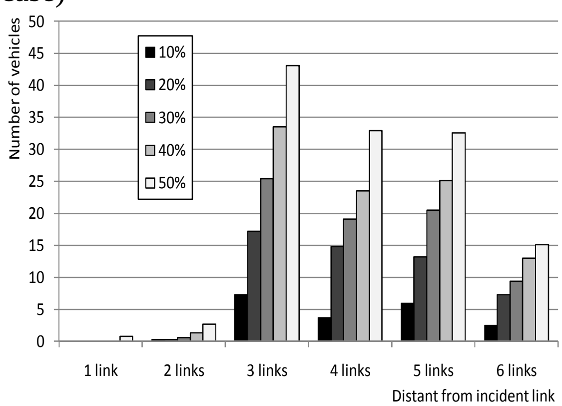
Figure 40 shows the spatial characteristics of re-routing vehicles in 500m radio range case for two traffic flow rate cases. If the location at which vehicles initially choose to re-route was uniformly distributed over the network links in zones 3 or 4 would be expected to contain more re-routing vehicles due to their larger area. However, zone 4 has a very small number of re-routing vehicles in the 300vph case (Figure 40 (a)) (more specifically addressed in Figure 41) and the travel time saving pattern is also irregular (Figure 40 (b)). However, zones 3, 4 and 5 have the most re-routing vehicles in 514vph case (Figure 40 (c)) and zones 3, 5, and 6 saved more time from the traffic incident because the outer and network-entering zones have more opportunities to choose less incident-involved routes than the inner zones. Also, while the significant travel time saving of vehicles re-routing in the zone 2 in 300vph case (Figure 40 (b)) is interpreted as small number of vehicle re-routings that occurred in the beginning time period of the traffic incident and due to the direct congestion effect of the incident, much less time savings of re-routing vehicles in the zone 2 in 514vph case (Figure 40 (d)) is because they re-routed in the less system-efficient time period and with the indirect incident effect.



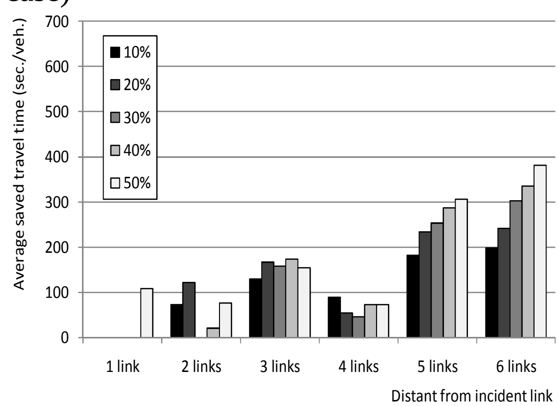
(a) Number of re-routing vehicles (300vph case)



(b) Average travel time savings (300vph case)



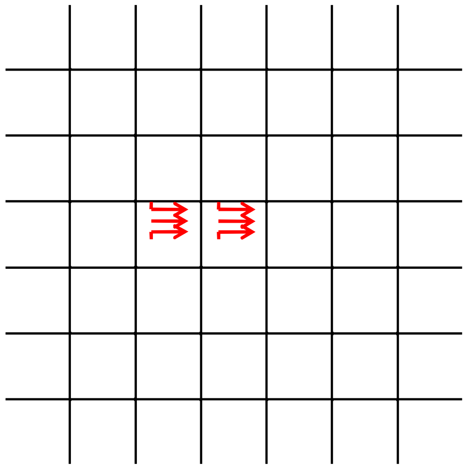
(c) Number of re-routing vehicles (514vph case)



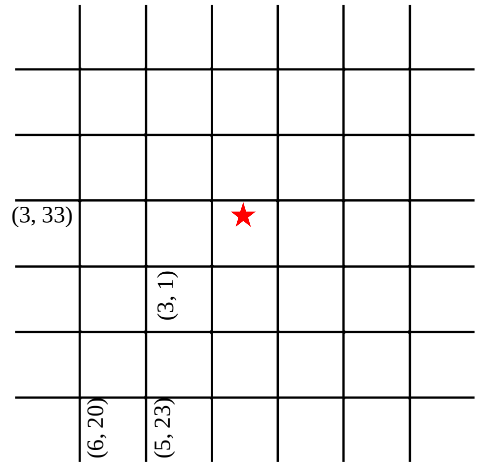
(d) Average travel time savings (514vph case)

Figure 40: Spatial Analysis of Vehicle Re-routing and Average Travel Time Savings

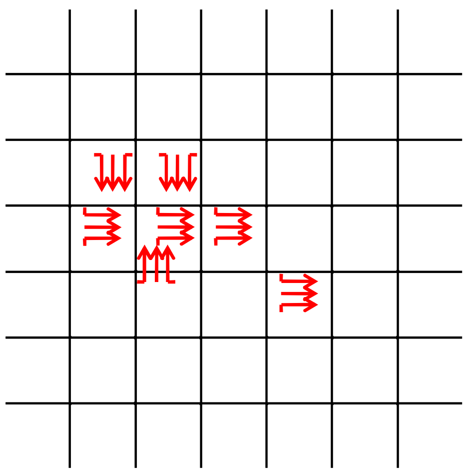
Figure 41 demonstrates the relationship between the traffic incident location and the congestion alert and route update locations for the 1st replicate run of the (300, 500, 50) and (514, 500, 50) scenarios. As previously stated the traffic incident occurs on the eastbound link in the center and is in effect from 1000sec to 2000sec, with one vehicle released every 90 seconds. As traffic demand increases, the incident more adversely affects vehicle travel and triggers more widespread re-routings. Most route updates and re-routings are implemented on the network-entering links. For example, six congestion messages in the 300vph case (Figure 41 (a)) brought about re-routings in the west-south side. Particularly, three relevant entering links have more re-routing vehicles (i.e., (3, 33), (6, 20), and (5, 23)) than the inner links. Therefore, at the low traffic demand case the route update locations are highly dependent on the location and direction of the incident links (Figure 40 (a)). Similarly, at the high traffic demand most re-routings have been identified on the entering links, however they are more spatially distributed throughout the network than the low flow rate case due to the spread of congestion resulting in the issuing of traffic congestion messages at more locations.



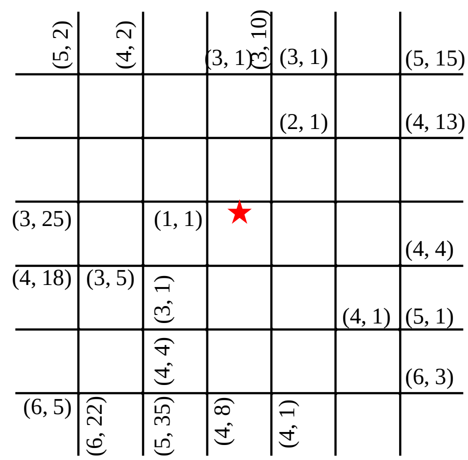
(a) Congestion alerts (300, 500, 50)



(b) Spatial re-routing pattern (300, 500, 50)



(c) Congestion alerts (514, 500, 50)



(d) Spatial re-routing pattern (514, 500, 50)

Figure 41: Traffic Congestion Alert Links and Spatial Re-routing Patterns

Note: star = eastbound incident location, arrow = congested links with congestion message for communication, (#, ##) = (area number, number of re-routing vehicles)

7.5 Summary

This chapter investigates the system performance of the advanced GATIS-V2V in a typical notional 6X6 urban grid network, with various scenarios composed of three system parameters. Prior to the actual investigation, three key modules are tested for reasonable system outputs result from varying system parameters. The vehicle communication module has been tested in terms of number of communication groups, average participating vehicles in one communication group, data dissemination speed, and average number of links whose travel times are saved in the individual participating vehicles. As traffic demand, radio range, and penetration ratio increase, the number of communication groups decreases, average number of participating vehicles increase, and data is disseminated more quickly. In addition, the frequent establishment and breaking of communication links explains that almost same amount of links are saved in individual participating vehicles every system update time interval with different traffic demand and radio range cases, not with the radio range.

The on-board database management module has been verified with number of (instant) re-routing vehicles. Timely update of traffic incident messages in the on-board database generated different numbers of re-routing vehicles subject to the various system parameter scenarios, with the exception of radio range. Lastly, the cognitive and actual travel time of the system-guided route has been compared for DRGS module verification. Approximately 80% and slightly over 50% of re-routing vehicles experienced less travel time or somewhat longer travel time (up to 20% greater) than the cognitive travel time for 300vph and 514vph cases, respectively. As expected, the traffic flow and penetration ratio are important factors influencing the associated number of re-routing vehicles. These results proved that three key modules in the advanced GATIS-V2V generally behave in an intuitive and a support their further use.

Utilizing these three verified modules, the performance of the advanced GATIS-V2V model has been evaluated with respect to the travel time difference of individual vehicles between no-communication and communication models. At the aggregated level participating and non-participating vehicles saved more time at the higher flow rates and penetration ratios, with the radio range having minimal impact. Focusing on the travel time difference of (instant) re-routing vehicles, lower traffic flow cases saved more time than higher traffic flow ones. This is because a relatively small number of vehicles in 300vph case re-route during the most system-efficient time period (i.e., the early time of the traffic incident) but more vehicles in 514vph case re-route during less system-efficient time period, after the incident is resolved. Also, normally re-routings on the network-entering links saved more travel time than any other places inside the network except the case where the direct effect of traffic incident triggers vehicle re-routings during the effective incident time period (e.g., travel time savings at 20% penetration ratio in Figure 40 (b)) and the location and direction of the incident link determines the spatial distribution of re-routing vehicles.

CHAPTER 8 CENTRALIZED AND DECENTRALIZED TRAVELER INFORMATION MODEL COMPARISON

8.1 Introduction

The V2V communication system is one platform of IntelliDrive^{SM}, a suite of technologies and applications using wireless communications to improve the traffic safety, mobility, and energy-efficiency [113]. Most transportation applications envisioned with V2V communication system are devoted to the traffic safety but vehicle re-routing application might be implemented through the V2R communication system relaying the real-time traffic information to the TMC using the roadside equipment (RSE). This research names the centralized traffic information system using Vehicle-to-Roadside (V2R) communication system as the GATIS-V2R model. Traditionally traffic management and traveler information systems are actualized on the regional-level freeway or major arterials, but this research investigates the basic characteristics of the GATIS-V2R model implemented in the typical urban grid network and compares it with the GATIS-V2V model.

8.2 Difference between GATIS-V2V and GATIS-V2R Models

The most critical difference between GATIS-V2V and GATIS-V2V models is the location where the data collection, database, and route update processes are implemented. Individual participating vehicles in the GATIS-V2V model can be referred to as the moving TMCs, but the GATIS-V2R model conducts all required processes in one TMC.

The system performance of the GATIS-V2R model becomes dependent on the density of the RSE and their communication radio range.

The GATIS-V2R model operated under an ideal communication environment constantly contains and updates the up-to-date network-wide traffic state information, so the updated database and sought routes might be more accurate than the GATIS-V2V model updating the local traffic state information because of the possibly limited communication capability. Therefore, the two types of model would have slightly different vehicle re-routing patterns and traffic incident identification. Thus the output of the GATIS-V2R model can be used as a benchmark to evaluate the GATIS-V2V model performance. On the other hand, as mentioned in Chapter 5, in spite of the potentially less accurate output of the GATIS-V2V model the possible non-trivial time lags in the GATIS-V2R model between the occurrence of the non-recurrent traffic state and provision of the responsive new route [107-109] due to intensive computational resources to constantly trace time and location of all participating vehicles and heavy predictive input information for the large network can be overcome by the GATIS-V2V model.

Also, some delay of the update of traffic congestion messages in the GATIS-V2V model due to the communication restriction, particularly at low traffic flow, smaller radio range, and low penetration ratio might not cause significant system performance discrepancy from the GATIS-V2R model output due to the high mobility and multi-hop data dissemination method with the participating vehicles. Obviously, the more communication-favorable scenarios (i.e., high flow rate, large radio range, and high penetration ratio) in the GATIS-V2V model forms a single large communication group containing all participating vehicles in the network should generate the same model behavior as the GATIS-V2R model. Hence, it is interesting to investigate the system output difference between two types of model and how much the GATIS-V2V model can pursue the GATIS-V2R model.

8.3 Experimental Design

The performance of the GATIS-V2R model has been investigated by implementing it in the same 6X6 urban grid traffic network with the same traffic incident case used in Chapter 7. The mixed O-D/Route information of the communication radio range 500m in the GATIS-V2V model has been reused to run the GATIS-V2R model for investigating its characteristics. The parameter values of K and I factors are 3 and 20% and the minimum sample size is 2 for each links. Most performance metrics used for the model verification and evaluation have been observed again. This research assumes that the entire network is covered by the radio range of the RSEs, so no signal interference or data loss in communications are pursued in the GATIS-V2R model.

8.4 Characteristics of the GATIS-V2R Model

The characteristics of the GATIS-V2R model have been investigated by comparing the metrics derived from the GATIS-V2R and GATIS-V2V models, especially focusing on the behavior of three key system modules.

8.4.1 Vehicle-to-Roadside Communication

The communication function of the GATIS-V2R model can be tested in terms of the number of links whose travel times were saved in the STM of the TMC every system update time interval (i.e., 3min in this study). Figure 42 compares the average number of links covered by the TMC and participating vehicles in the individual communication groups every system update time interval with varying penetration ratios for the GATIS-V2R and GATIS-V2V models, respectively. The 500m radio range case of the GATIS-V2V model formed one communication group for 300vph and 514vph every system update time interval, so no difference in the communication area is identified between two models. Considering that the maximum number of links in the network is 720 links, approximately 20% to 40% area of the large network is available for updating the database and routes in the GATIS-V2R and GATIS-V2V models, depending on the traffic flow and penetration ratios.

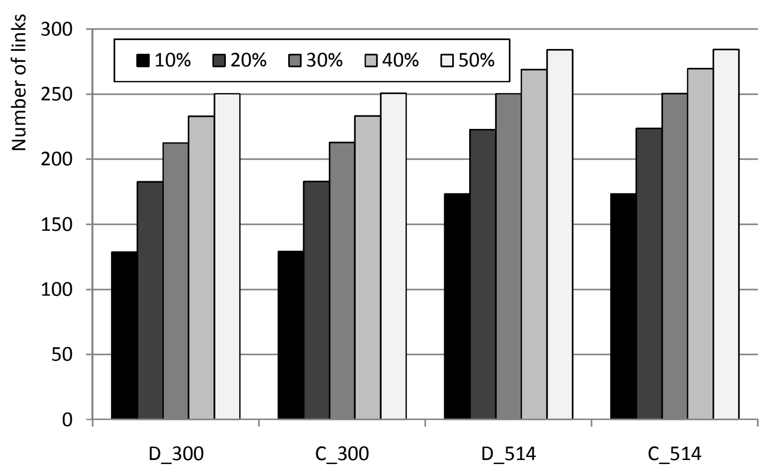


Figure 42: Number of Links Covered by ATIS Type

Note: D_### = GATIS-V2V (decentralized) model with ###vph / C_### = GATIS-V2R (centralized) model with ###vph

8.4.2 Database Management Strategy

As addressed earlier, the timely and efficient update of the traffic congestion information in the STM is very important task in the GATIS-V2R and GATIS-V2V models because updated and estimated traffic state information is utilized as an input data to DRGS. Thus, the number of vehicle re-routings is reliant on the on-board traffic database management strategy. Also, since all participating vehicles in the GATIS-V2V model and the TMC in the GATIS-V2R model update their database and routes as soon as new traffic congestion messages are available, all vehicle re-routings are instantly determined rather than in the scheduled fashion. Figure 43 provides the number of (instant) re-routing vehicles of the GATIS-V2R model for two different traffic flows and compares it with the GATIS-V2V model. The GATIS-V2R model clearly distinguishes the different number of vehicle re-routings subject to the traffic flow and penetration ratio, proving that the traffic information database in the TMC is successfully managed. In addition, the GATIS-V2V model generates almost identical number of re-routing vehicles compared to the GATIS-V2R model, implying that individual participating vehicles in the GATIS-V2V model seems to emulate the database management strategy implemented in the TMC.

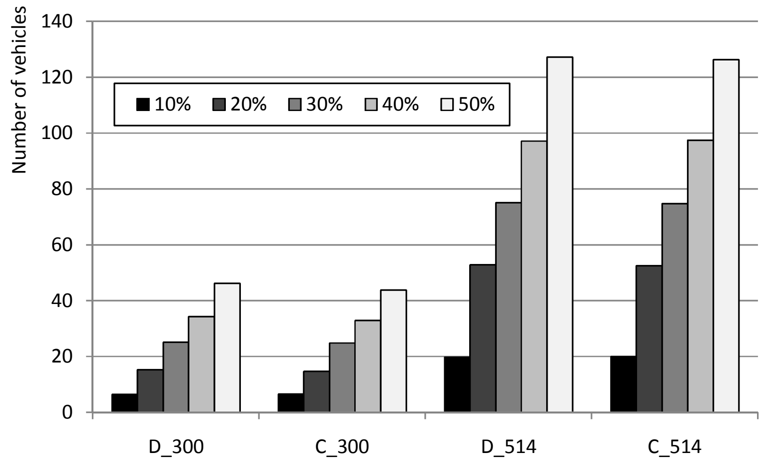
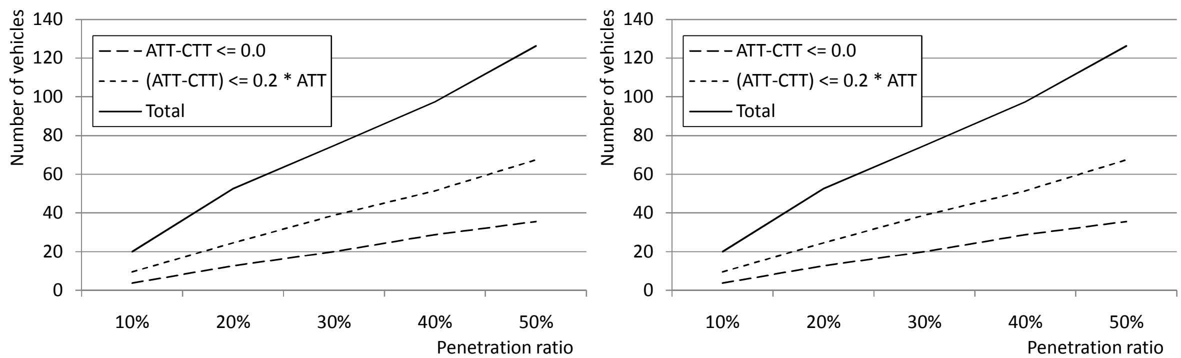


Figure 43: Number of (Instant) Re-routing Participating Vehicles by ATIS Type
Note: D_### = GATIS-V2V (decentralized) model with ###vph / C_### = GATIS-V2R (centralized) model with ###vph

8.4.3 Dynamic Route Guidance System

The cognitive travel time (i.e., historical travel time) of the re-routing vehicles derived from the GATIS-V2R model has been compared with the actual travel time to evaluate the accuracy of the model output. Figure 44 provides the number of (instant) re-routing vehicles of which the actual travel time of the system-guided route is shorter than or equal to the cognitive travel time and also no more than 20% longer in the GATIS-V2R model. These values are compared to the values for the V2V system described in Chapter 7 (Figure 35). Approximately 60% and 30% of re-routing vehicles saved more than 0 seconds by traveling on the system-guided route for 300vph and 514vph, respectively and about 90% of re-routing vehicles from the GATIS-V2R model fall into the patient driver group in 300vph case. Approximately 50% of re-routing vehicles in the higher traffic demand case experienced over 20% longer than the system-informed travel time (Figure 44 (b)). Although ATMS and ATIS attempt to achieve their ultimate goal (i.e., improvement of mobility) under high traffic demand conditions, Figure 44 demonstrates that efficient network-wide management of traffic and provision of more accurate traffic state estimation is very difficult as alternative routes are limited, re-routing vehicles can form new congestions near to the incident link, and travel times can be highly variable. The GATIS-V2V model follows the exact patterns of traffic flow and penetration ratio-dependent travel time estimation accuracy of the GATIS-V2R model.



(a) 300vph case (b) 514vph case

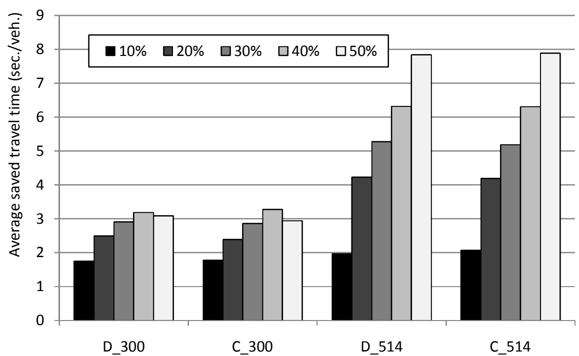
Figure 44: Actual and Historical Travel Time Difference of Re-routing Vehicles in the GATIS-V2R Model

However, the performance of the GATIS-V2R and GATIS-V2V models could be reinforced with more comprehensive traffic information (i.e., traffic signal information, queue distance, vehicle turning volumes, etc.) in searching for system-optimal routes.

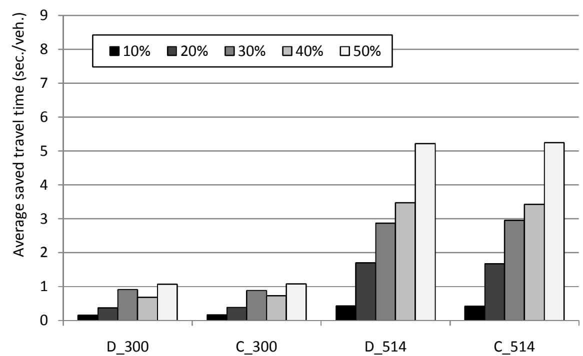
8.5 GATIS-V2R and GATIS-V2V Model Performance Comparison

Travel time savings as model output have been investigated and compared between the GATIS-V2R and GATIS-V2V models for the participating and non-participating vehicles and (instant) re-routing participating vehicles. Then, the temporal and spatial vehicle re-routing and travel time saving patterns have been studied for both models.

Figure 45 shows the average travel time savings of participating and non-participating vehicles for two traffic flow cases of the GATIS-V2R and GATIS-V2V models with varying penetration ratios. While the travel time savings of participating vehicles result from the vehicle re-routings to avoid the traffic incident route, non-participating vehicles also saved their time due to the reduced delay of the traffic incident-involved vehicles.



(a) Participating vehicles



(b) Non-participating vehicles

Figure 45: Average Travel Time Savings of Vehicles by ATIS Type

Note: D_### = GATIS-V2V (decentralized) model with ###vph / C_### = GATIS-V2R (centralized) model with ###vph

Separating the re-routing participating vehicles, Figure 46 reveals that 300vph case saved more time per vehicle than 514vph case like the GATIS-V2V model output and the travel time savings pattern of the GATIS-V2R model is almost the same as the GATIS-V2V model, showing that the GATIS-V2V model, with the given assumptions, could take the place of the GATIS-V2R model.

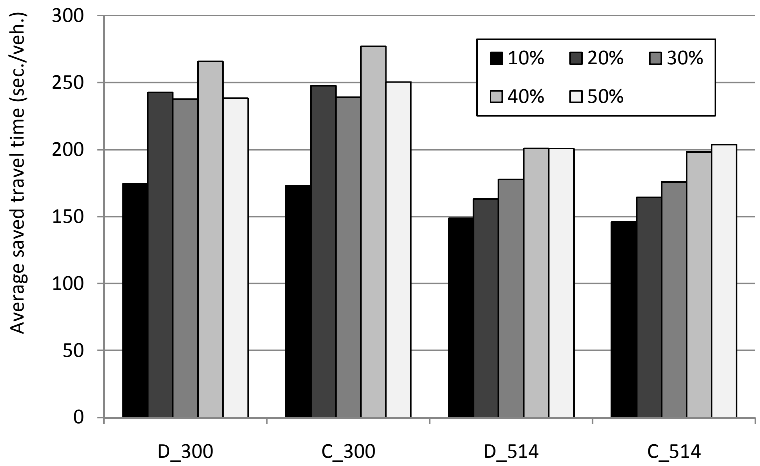
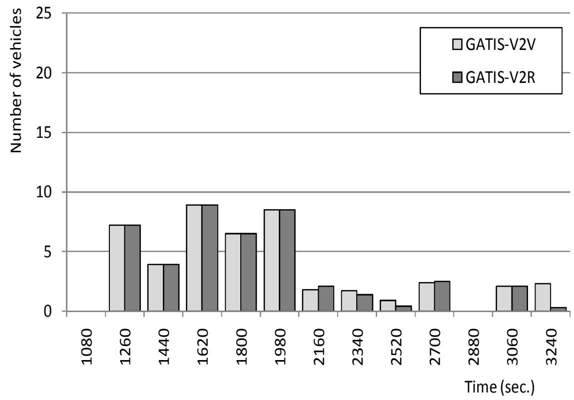


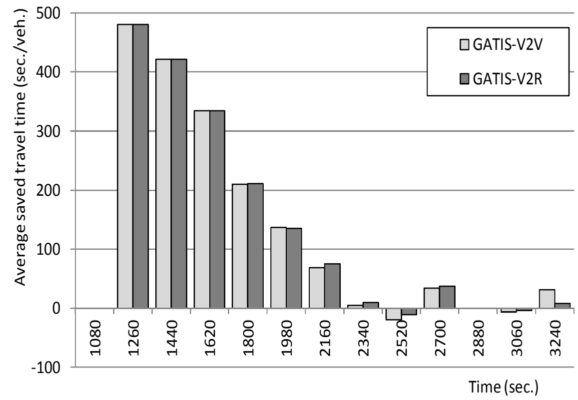
Figure 46: Average Travel Time Savings of (Instant) Re-routing Participating Vehicles by ATIS Type

Note: D_### = GATIS-V2V (decentralized) model with ###vph / C_### = GATIS-V2R (centralized) model with ###vph

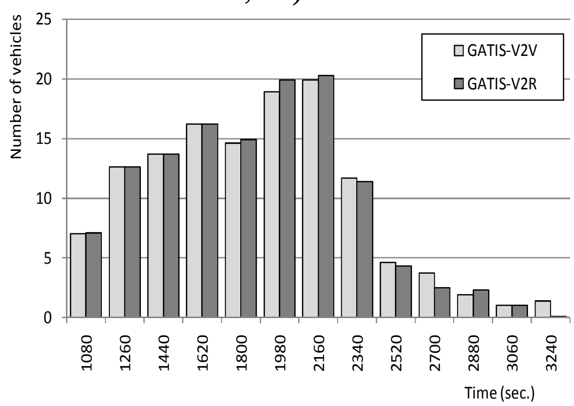
Figure 47 and Figure 48 show the temporal and spatial analysis of the vehicle re-routing and travel time savings patterns in the GATIS-V2R model and compare them with the GATIS-V2V model. The (300, 500, 50) and (514, 500, 50) cases temporally re-route almost the same number of vehicles and save the similar amounts of time, with a small variance after the traffic incident is resolved (Figure 47). Also, the spatial distribution of re-routing vehicles and travel time savings of the GATIS-V2R model almost exactly matches with the GATIS-V2V model in Figure 40 (Figure 48). This output confirms that temporally and spatially the GATIS-V2V model generates almost identical system performance to the GATIS-V2R model in saving travel time of vehicles, for the given GATIS-V2V model assumptions.



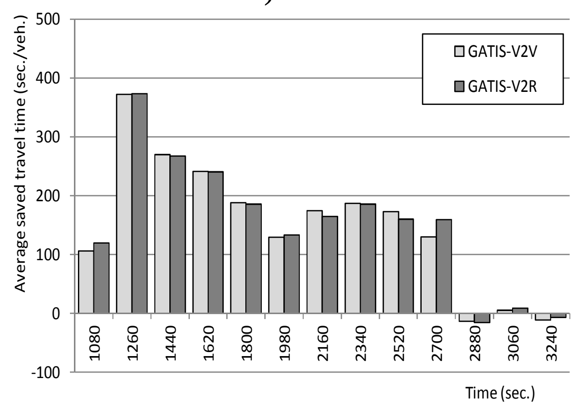
(a) Number of re-routing vehicles (300, 500, 50) case



(b) Average etravel time savings (300, 500, 50) case

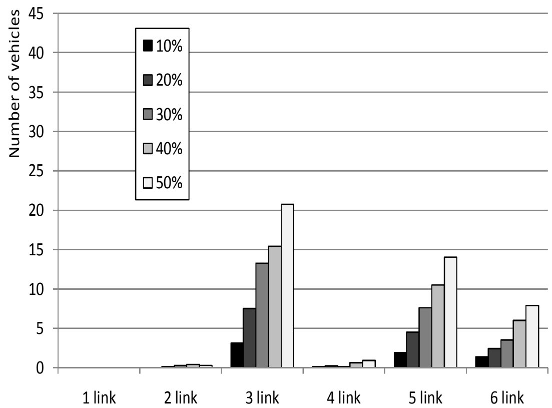


(c) Number of re-routing vehicles (514, 500, 50) case

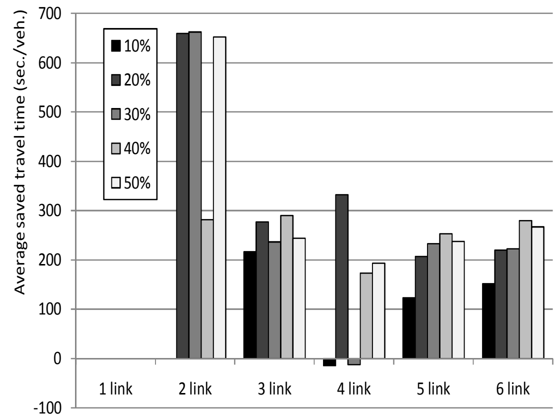


(d) Average travel time savings (514, 500, 50) case

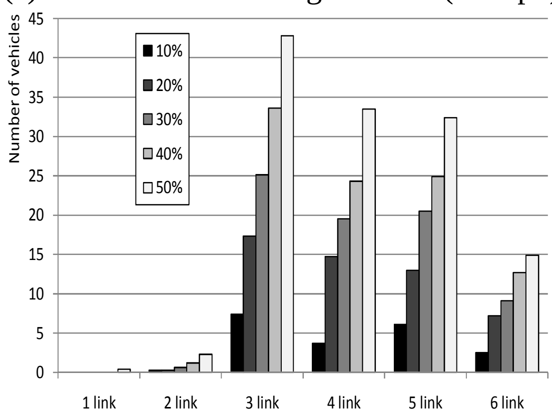
Figure 47: Temporal Analysis of Vehicle Re-routing and Average Travel Time Savings between Two Traffic Information Systems



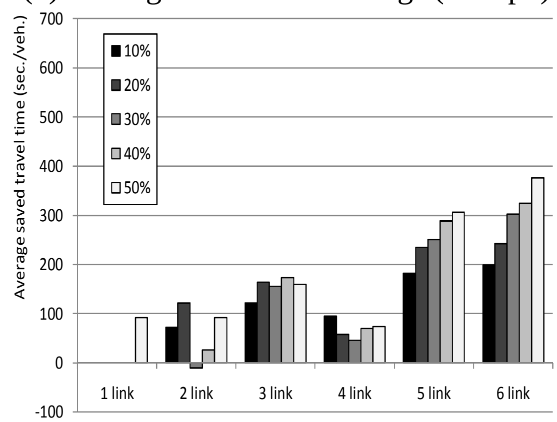
(a) Number of re-routing vehicles (300vph)



(b) Average travel time savings (300vph)



(c) Number of re-routing vehicles (514vph)



(d) Average travel time savings (514vph)

Figure 48: Spatial Analysis of Vehicle Re-routing and Average Travel Time Savings of the GATIS-V2R Model

Note: X-axis is the distance from participating vehicles updating and re-routing to the incident link.

8.6 Summary

This research developed the centralized traveler information system using V2R communication system (i.e., the GATIS-V2R model), investigated its characteristics in the typical urban grid network, and compared it with the GATIS-V2V model output.

The most significant distinction between the GATIS-V2R and GATIS-V2V models is the location where the system is updated and data size to be used for the system update.

Additionally, the GATIS-V2R requires expensive infrastructure investments and operational cost with the limited scalability confined to the urban area. In spite of the fundamental difference, the verification process of the three underlying system modules in the GATIS-V2R model showed exactly the same results as the GATIS-V2V model, even at the low flow rate, narrower radio range, and low penetration ratios. Furthermore, all tested metrics of the GATIS-V2R model indicated that the system performance of both models is almost identical regardless of varying traffic demand and penetration ratios. Therefore, decentralized ATIS model using V2V communication system can be a reasonable alternative to the fixed infrastructure-based ATIS model.

CHAPTER 9 CONCLUSIONS

This chapter summarizes the findings from this research in Section 9.1. Major contributions are described in Section 9.2 and the research limitations and future work are addressed in Section 9.3.

9.1 Summary of Findings

This research developed the Advanced Traveler Information System using Vehicle-to-Vehicle communication system (GATIS-V2V) under an ideal communication environment. The GATIS-V2V model consists of three basic system modules: vehicle communication, on-board database management, and a dynamic route guidance system. The performance of GATIS-V2V has been further enhanced by three complementary functions: autonomous automatic incident detection (AAID) algorithm, minimum sample size, and drivers' route choice rule. The significant distinction between this research and other relevant research on the application of vehicle-to-vehicle communication to transportation system operations is the development of a complete ATIS model, implementation the modules and functions above, not a partial ATIS model consider only a small portion of an ATIS system, and testing of the model on a signalized network.

This study investigated the characteristics of the proposed GATIS-V2V model and evaluated its performance with an off-the-shelf microscopic simulation model (VISSIM) in the simple network (non-signalized and signalized) and in typical Manhattan style urban grid network (signalized), under the traffic incident traffic state. Lastly, this research compared the performance of GATIS-V2V model with that of the GATIS-V2R, exploring the possibility the GATIS-V2V approach replacing GATIS-V2R. The findings of this research are as follows:

9.1.1 Non-signalized Simple Network with the Basic GATIS-V2V Model

- Time delay between the incident start and its effect influencing the GATIS-V2R model or GATIS-V2V model route travel time estimates resulted in some participating vehicles not receiving updated travel time estimates in a sufficiently timely manner to allow them to avoid the incident-related congestion.
- Some subset of participating vehicles must traverse each link to maintain reasonable travel time estimates, potentially requiring a participating vehicle to use a highly inefficient route.
- All three proposed system (GATIS-V2R-1, GATIS-V2R-2, and GATIS-V2V models) provided travel time saving benefits to both participating and non-participating vehicles. Especially, the average travel time savings per vehicle of both models reached the marginal travel time saving after about 60% penetration ratio in the simple traffic network. In the mid and higher range volume scenarios the GATIS-V2V provided equal or better performance as that of the GATIS-V2R and in the low demand scenario the GATIS-V2V is unable to create sufficient communication groups to effectively pass the data, thus the GATIS-V2R proves a superior approach.

9.1.2 Non-signalized Simple Network with the Advanced GATIS-V2V Models

- Dynamic real-time traffic data dissemination under good communication conditions (i.e., larger radio range) in the basic GATIS-V2V model (Case NABC) does not always outperforms ATIS model with less favorable communication conditions due to unreliable data propagation.
- Shortening the time delay between the incident start and its effect influencing route travel time estimates is very important to improving system performance.
- The drivers' re-routing rule fundamentally influences system performance, controlling the re-routing patterns before the incident, and when combined with the congestion alert system, results in consistent and robust performance.
- The system performance of the minimum sample size rule (Case B) is potentially less realistic and less efficient due to route updates continuing to depend on the historical link travel time when limited new data is available.
- As the penetration ratio and communication radio range increase, the participating and non-participating vehicles save more travel time, over nearly all ATIS system configurations. Particularly, the average travel time savings per vehicle reached the marginal effect after about 60% penetration ratio in the simple traffic network.

9.1.3 Signalized Simple Network with the Advanced GATIS-V2V Models

- The travel time variability due to the traffic signal effect is reflected in the historical link travel time and the minimum sample size rules derived from the heuristic method designed in this study prove unrealistic, resulting in the use of a simplified minimum sample size of rule, i.e., two or more data points must be available.

- The basic ATIS model (i.e., NABC case) performance is mainly influenced by traffic signal parameters (i.e., historical link travel time) and the location of the non-recurrent traffic states, but the advanced models coupled with *K* and *I* factors are constant, consistent, and robust in their performance.
- As the penetration ratio and communication radio range increase, the participating and non-participating vehicles save more travel time, over nearly all ATIS system configuration. Like the non-signalized simple traffic network, after around 60% penetration ratio the system reached the marginal effect in the average travel time savings per vehicle in the signalized simple traffic network.
- The sensitivity of complementary functions (mainly *K* and *I* factors) to the travel time savings of the re-routing vehicles with Monte Carlo simulation method found that triggering vehicle re-routings at 20% or 30% increase in relative travel time saving from the current route seems to be reasonable in the signalized traffic network (*I* factor).
- Low *K* factor value might issue too many false alarms of the traffic congestion due to travel time variability at the signalized traffic network and high *K* factor value will delay the non-recurrent traffic state update. The sensitivity analysis of *K* factor to the advanced GATIS model performance suggests utilizing a *K* factor of 2 or 3.

9.1.4 Signalized Urban Grid Network with the Advanced GATIS-V2V Models

- The verification process of vehicle communication module found that as traffic demand, radio range, and penetration ratio increase, the number of communication groups decreases and traffic data is disseminated faster. In addition, frequent establishment and breaking of communication links result in nearly the same number of links being saved in the STM of individual participating vehicles every system update time interval.
- The on-board database management module has been verified and found that the timely update of traffic incident messages in the on-board database generated different number of re-routing vehicles, subject to the various system parameter scenarios, except the radio range.
- DRGS module verification process indicates that approximately 80% and slightly over 50% of re-routing vehicles experienced a travel time under 120% of the cognitive travel time for 300vph and 514vph cases, respectively. Higher traffic demand results in more interactions with neighboring vehicles and additional traffic congestion on the links adjacent to the incident link.
- The GATIS-V2V model performance has been evaluated with respect to the travel time savings. Participating and non-participating vehicles saved more time at the higher flow rate and penetration ratio. Radio range was not an important factor affecting the system performance because the radio range restriction has been easily overcome by fast mobility and multi-hop communication of participating vehicles.

- Focusing on the travel time difference of (instant) re-routing vehicles, lower traffic flow cases saved more time than higher traffic flow on average because in the lower demand case fewer vehicle rerouted, most of which during the initial period after the incident when time savings was the most significant. In the higher demand case re-routing also occurred during this initial time period but also during less system-efficient time periods after the incident is resolved and residual congestion effects still existed.
- Most re-routings decisions occurred on the network-entering links and the location and direction of the incident link determines the spatial distribution of re-routing vehicles.

9.1.5 Signalized Urban Grid Network with the GATIS-V2V and GATIS-V2R Models

- The most critical difference between the GATIS-V2R and GATIS-V2V models is the location where the system is updated and data size to be used for system update.
- The verification process of the three underlying system modules in the GATIS-V2R model matched the characteristics of the GATIS-V2V model.
- All tested metrics of the GATIS-V2R model indicated that the system performance of both models, for the given GATIS-V2V model assumptions, is almost identical regardless of varying traffic demand and penetration ratios, implying that decentralized ATIS model using V2V communication system can be a reasonable alternative to the fixed infrastructure-based ATIS model.

9.2 Contributions

This research developed and evaluated an ATIS model using more affordable and available cutting-edge technologies, such as wireless communication between vehicles, as a possible alternative to the fixed infrastructure-based ATIS model. The major contributions of this research are summarized as follows:

- This research developed a comprehensive real-time ATIS model using V2V communication, incorporating three key modules: vehicle communication, on-board database management strategy, and dynamic route guidance system.
- This research provided a feasible test bed and operational guidelines of RT-ATIS using V2V communication system with an off-the-shelf microscopic simulation model.
- This research investigated the characteristics of RT-ATIS using V2V communication with three underlying system parameters (i.e., traffic flow, communication radio range, and penetration ratio).
- This research implemented and investigated system performance-enhancing functions (i.e., autonomous automatic incident detection algorithm, minimum sample size, and drivers' route choice role) and defined their parameter values.
- This research provided a possibility to replace the fixed infrastructure-based traffic information system with ITS strategy using vehicle communication.
- This research demonstrated, for the given model and network assumptions, that penetration ratios do not need to exceed 50% to 60% for instrumented vehicles to

achieve the full benefits of the information system in terms of the average travel time savings per vehicle. Thus, an implementation plan that realizes on the introduction of technology through new vehicles could provide a reasonable means for system introduction.

- This research has shown that an incident detection system must be a key attribute of ATIS system. The failure to rapidly detect incidents and immediately pass this information to participating vehicles will significantly reduce the effectiveness of any system.
- Further, the characteristics of the incident detection system will likely be based on historic or expected travel times. An incident detection system that results in false alarms will result in unnecessary re-routing while a detection algorithm that is too conservative will result in significant delays in the notification of participating vehicles.
- This research has shown that the introduction of boundedly rational driving rules will impact driver's route choice selection and therefore should be included in any ATIS development and evaluation.

9.3 Research Limitations and Future Research

This research used simplified communication attributes such as limited radio range, broadcasting data dissemination scheme with flooding, no signal drop, round shape of communication signal, and no media access control method even in the urban area. Future research should modify these parameters with more realistic values.

For on-board database management strategy the simple average method has been used to predict the short-term link travel time, so more efficient and advanced algorithms should be explored. Also, at the low penetration ratio the travel time records are not likely to meet the minimum sample size condition established based on the historical link travel time and system update consistently relies on the historical link travel time. Thus, more studies should be performed for the reliability of traffic information saved in individual participating vehicles. Additionally, more advanced and realistic drivers' route choice model needs to be used in the dynamic route guidance system.

Furthermore, this study used pre-determined design parameter sets for system development and evaluation. For example, 3-minute system update time interval, average travel time over the previous four time bins (i.e., data life span), constant vehicle generation headway dependent on given traffic flow, no trip chain consideration, etc. Thus, to get more insights into traveler information system using V2V system sensitivity analysis of aforementioned parameters to system performance should be investigated.

More various traffic control methods (i.e., actuated or semi-actuated traffic signal controls) and the effect of the incident location and its severity (i.e., incident duration) in the large network should be investigated as well.

REFERENCES

1. Keever, D., Shimizu, M., Seplow, J., *Data Fusion for Delivering Advanced Traveler Information Services*. 2003: Federal Highway Administration. 164 p.

2. Administration, R.a.I.T. *ITS Overview*. 2009 11/20/2009 [cited 2009 12/01]; Available from: http://www.its.dot.gov/its_overview.htm.

3. Kim, H., *A Simulation Framework for Traffic Information Dissemination in Ubiquitous Vehicular Ad Hoc Networks*, in *Civil and Environmental Engineering*. 2007, University of Maryland: College Park. p. 122p.

4. Xu, H. and M. Barth, *Travel Time Estimation Techniques for Traffic Information Systems Based on Inter-vehicle Communications.* Transportation Research Record, 2006(1944): p. 72-81.

5. Wai, C. and C. Shengwei, *Ad Hoc Peer-to-Peer Network Architecture for Vehicle Safety Communications.* Communications Magazine, IEEE, 2005. 43(4): p. 100-107.

6. Tsugawa, S., *Issues and Recent Trends in Vehicle Safety Communication Systems.* International Association of Traffic Safety Sciences, 2005. 29(1): p. 7-15.

7. Chisalita, L. and N. Shahmehri. *A Peer-to-Peer Approach to Vehicular Communication for the Support of Traffic Safety Applications, 2002. Proceedings. The IEEE 5th International Conference on*. 2002.

8. Sen, A., et al., *Frequency of Probe Reports and Variance of Travel Time Estimates.* Journal of Transportation Engineering, 1997. 123: p. 290.

9. Lorkowski, S., P. Mieth, and R. Schafer, *New ITS Applications for Metropolitan Areas Based on Floating Car Data*, in *European Conference of Transport Research Institutes (Young Researchers Seminar)*. 2005: France.

10. Hris, N.T.L., *Safety Applications of Intelligent Transportation Systems in Europe and Japan.* Transportation Research, 2009. 5: p. 19AM.

11. Mineo, T., M. Jay, and B. Rajive, *Effects of Wireless Physical Layer Modeling in Mobile Ad Hoc Networks*, in *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking; computing*. 2001, ACM: Long Beach, CA, USA.

12. Masahi, S., et al., *Evaluation of Inter-Vehicle Ad Hoc Communication Protocol*, in *Proceedings of the 19th International Conference on Advanced Information Networking and Applications - Volume 1*. 2005, IEEE Computer Society.

13. Dhoutaut, D. and I.G. Lassous. *Performance of a Multi-hops Configuration with 802.11: from Simulation to Experimentation, Indoor and Mobile Radio Communications, 2004. PIMRC 2004. 15th IEEE International Symposium on*. 2004.

14. Park, B., *Transportation Management System Performance Monitoring, Evaluation, and Reporting - a Technical Handbook*. 2005, Department of Civil Engineering in University of Virginia: Charlottesville. p. 161p.

15. Harri, J., F. Filali, and C. Bonnet. *A Framework for Mobility Models Generation and its Application to Inter-vehicular Networks*. in *Wireless Networks, Communications and Mobile Computing, 2005 International Conference on*. 2005.

16. Kumar, S., V.S. Raghavan, and J. Deng, *Medium Access Control Protocols for Ad Hoc Wireless Networks: A survey.* Ad Hoc Networks, 2006. 4(3): p. 326-358.

17. Kim, J., *Realistic Mobility Modeling and Simulation for Mobile Wireless Network in Urban Environments*, in *Electrical and Computer Engineering*. 2005, University of Delaware: Delaware. p. 70p.

18. Haerri, J., Filali, F., Bonnet, C., *Mobility Models for Vehicular Ad Hoc Networks: a Survey and Taxonomy*. Communications Surveys & Tutorials, IEEE, 2008. 10.

19. Karnadi, F.K., M. Zhi Hai, and L. Kun-chan. *Rapid Generation of Realistic Mobility Models for VANET*. in *Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE*. 2007.

20. Mahajan, A., Potnis, N., Gopalan, K., Wang A. A., *Evaluation of Mobility Models for Vehicular Ad-hoc Network Simulations*. 2005, Florida State University: Tallahassee. p. 13.

21. Bohacek, S., et al., *The UDel Models - MANET Mobility and Path Loss in an Urban/Suburban Environment*. 2004, University of Delaware: Delaware. p. 15pages.

22. Sridhara, V. and S. Bohacek, *Realistic Propagation Simulation of Urban Mesh Networks.* Computer Networks, 2007. 51(12): p. 3392-3412.

23. Jardosh, A., et al. *Towards Realistic Mobility Models For Mobile Ad hoc Networks*. 2003. San Diego, CA., United States: Association for Computing Machinery.

24. California, U.o.S. *Radio Propagation Models*. 2007 [cited 2008 March 3]; Available from: http://www.isi.edu/nsnam/ns/doc/node216.html.

25. Peiyan, Y. and L.I. Layuan, *Performance Evaluation and Simulations of Routing Protocols in Ad Hoc Networks*, in *Proceedings of the 2006 workshop on Broadband wireless access for ubiquitous networking*. 2006, ACM: Alghero, Italy.

26. Adler, C., *Information Dissemination in Vehicular Ad Hoc Networks*. 2006, University at Munchen: Munchen. p. 127pages.

27. Jaap, S., M. Bechler, and L. Wolf. *Evaluation of Routing Protocols for Vehicular Ad Hoc Networks in City Traffic Scenarios*. in *The 5th International Conference on Intelligent Transportation Systems Telecommunications (ITST)*. 2005. Brest, France.

28. Josh, B., et al., *A Performance Comparison of Multi-hop Wireless Ad Hoc Network Routing Protocols*, in *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking*. 1998, ACM: Dallas, Texas, United States.

29. Rui, J., V. Gupta, and C.V. Ravishankar. *Interactions between TCP and the IEEE 802.11 MAC protocol*. in *DARPA Information Survivability Conference and Exposition, 2003. Proceedings*. 2003.

30. Xu, H. and M. Barth. *A Transmission-interval and Power-level Modulation Methodology for Optimizing Inter-vehicle Communications*. 2004. Philadelphia, PA, United States: Association for Computing Machinery, New York, NY 10036-5701, United States.

31. Wischhof, L., A. Ebner, and H. Rohling, *Information Dissemination in Self-organizing Inter-vehicle Networks.* Intelligent Transportation Systems, IEEE Transactions on, 2005. 6(1): p. 90-101.

32. Michael, L.B. and M. Nakagawa. *Multi-hop for Inter-vehicle Communication over Multiple Lanes*. in *Intelligent Vehicles Symposium, 1996., Proceedings of the 1996 IEEE*. 1996.

33. Hui, F. and P. Mohapatra. *Experimental Characterization of Multi-hop Communications in Vehicular Ad Hoc Network*. 2006. Cologne, Germany: Association for Computing Machinery, New York, NY 10036-5701, United States.

34. Aziz, F.M., *Implementation and Analysis of Wireless Local Area Networks for High-Mobility Telematics*, in *Electrical Engineering*. 2003, Virginia Polytechnic Institute and State University: Blacksburg. p. 150.

35. Gupta, A., I. Wormsbecker, and C. Wilhainson. *Experimental Evaluation of TCP Performance in Multi-hop Wireless Ad Hoc Networks*. in *Modeling, Analysis, and Simulation of Computer and Telecommunications Systems, 2004. (MASCOTS 2004). Proceedings. The IEEE Computer Society's 12th Annual International Symposium on*. 2004.

36. Jerbi, M., S.M. Senouci, and M. Al Haj. *Extensive Experimental Characterization of Communications in Vehicular Ad Hoc Networks within Different Environments*. 2007.

37. Wu, H., Lee, J., Hunter, M., Fujimoto, R., Guensler, R. L., Ko, J., *Efficiency of Simulated Vehicle-to-Vehicle Message Propagation in Atlanta, Georgia, I-75 Corridor*. TRR, 2005(1910): p. 82-89.

38. Wu, H., Fujimoto, R., Riley, G., *Analytical Models for Information Propagation in Vehicle-to-Vehicle Networks*, in *Vehicular Technology Conference*. 2004. p. 4548-4552.

39. Schonhof, M., et al., *Coupled Vehicle and Information Flows: Message Transport on a Dynamic Vehicle Network.* Physica A: Statistical Mechanics and its Applications, 2006. 363(1): p. 73-81.

40. Kato, S. and S. Tsugawa. *Evaluation of Information Transmission over Inter-vehicle Communications with Simulation Studies*. in *Intelligent Transportation Systems, 2002. Proceedings. The IEEE 5th International Conference on*. 2002.

41. Jin, W.-L. and W.W. Recker, *Instantaneous Information Propagation in a Traffic Stream through Inter-vehicle Communication.* Transportation Research Part B: Methodological, 2006. 40(3): p. 230-250.

42. Artimy, M.M., W.J. Phillips, and W. Robertson. *Connectivity with Static Transmission Range in Vehicular Ad Hoc Networks*. in *Communication Networks and Services Research Conference, 2005. Proceedings of the 3rd Annual*. 2005.

43. Chen, Z.D., D. Vlah, and H.T. Kung. *Ad Hoc Relay Wireless Networks over Moving Vehicles on Highways*. 2001. Long Beach, CA, United States: Association for Computing Machinery.

44. Yang, X., *Assessment of A Self-Organizing Distributed Traffic Information System: Modeling and Simulation*, in *Civil Engineering Department*. 2003, University of California at Irvine: Irvine. p. 225.

45. Lomax, T., S. Turner, and R. Margiotta, *Monitoring Urban Roadways in 2000: Using Archived Operations Data for Reliability and Mobility Measurement.* Pub. No. FHWA-OP-02-029 (Washington: Federal Highway Administration, 2001).

46. Gold, D.L., et al., *Imputing Missing Values in ITS Data Archives for Intervals under 5 Minutes*. National Research Council (U.S.). Transportation Research Board. Meeting (80th : 2001 : Washington, D.C.). 8 p.

47. Nguyen, L.N. and W.T. Scherer, *Imputation Techniques to Account for Missing Data in Support of Intelligent Transportation Systems Applications*. 2003: University of Virginia, Charlottesville Research and Special Programs Administration. 124 p.

48. Ni, D., et al., *Multiple Imputation Scheme for Overcoming the Missing Values and Variability Issues in ITS Data.* Journal of Transportation Engineering, 2005. 131(12): p. 931-938.

49. Smith, B.L., W.T. Scherer, and J.H. Conklin, *Exploring Imputation Techniques for Missing Data in Transportation Management Systems*. 2003: Transportation Research Board. p. 132-142.

50. Nadeem, T., et al. *TrafficView: a Scalable Traffic Monitoring System*. in *Mobile Data Management, 2004. Proceedings. 2004 IEEE International Conference on*. 2004.

51. Dashtinezhad, S., et al. *TrafficView: a Driver Assistant Device for Traffic Monitoring Based on Car-to-Car Communication*. in *Vehicular Technology Conference, 2004. VTC 2004-Spring. 2004 IEEE 59th*. 2004.

52. Yang, X. and W.W. Recker, *Modeling Dynamic Vehicle Navigation in a Self-organizing, Peer-to-Peer, Distributed Traffic Information System.* Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 2006. 10(4): p. 185-204.

53. Rardin, R., *Optimization In Operations Research*. 1997: Prentice Hall. 919.

54.Wahle, J., et al., *A Dynamic Route Guidance System Based on real Traffic Data*. 2001: University of Queensland Teknillinen Korkeakoulu. Liikennelaboratorio Technische Universiteit Delft Gerhard-Mercator-Universitat Gesamthochschule Duisburg. p. 302-308.

55. Lee, J., *Evaluation of Smart Route Guidance Strategies under Vehicle Infrastructure Integration (vii),* in *Civil Engieering*. 2007, University of Virginia. p. 77p.

56. Lee, J., Park, B., *Evaluation of Vehicle Infrastructure Integration (VII) Based Routed Guidance Strategies under Incident Conditions*, in *TRB 2008 (87. Annual Meeting)*. 2008: Washington, DC (USA).

57. Krajzewicz, D., Boyom, D. T., Wagner, P., *Evaluation of the Performance of City-wide, Autonomous Route Choice Based on Vehicle-to-Vehicle-Communication*, in *TRB 2008 (87. Annual Meeting)*. 2008: Washington, DC (USA).

58. Liu, Y. and U. Ozguner, *Quantitative Evaluation of Inter-Vehicle Communication Effect in Highway Transportation from Micro and Macro Views*. Vol. 1. 2005: Inderscience Enterprises Limited. pp 152-180.

59. Laborczi, P., Torok, A., Vajda, L., Kardos, S., Gordos, G., Gerhath, G. *Vehicle-to-Vehicle Traffic Information System with Cooperative Route Guidance*. in *The 13th world congress on intelligent transport systems*. 2006. London, United Kingdom.

60. Guin, A., *An Incident Detection Algorithm Based on a Discrete State Propagation Model of Traffic Flow*. 2004.

61. Petty, K.F., et al., *A New Methodology for Evaluating Incident Detection Algorithms.* Transportation Research Part C, 2002. 10(3): p. 189-204.

62. Browne, R., et al., *Comparison and Analysis Tool for Automatic Incident Detection.* Transportation Research Record: Journal of the Transportation Research Board, 2005. 1925(-1): p. 58-65.

63. Parkany, E. and C. Xie, *A Complete Review of Incident Detection Algorithms and Their Deployment: What Works and What doesn't.* The New England Transportation Consortium, 2005.

64. Martin, P.T., et al., *Incident Detection Algorithm Evaluation.* Prepared for Utah Department of Transportation, University of Utah, 2001.

65. Thomas, N. and B. Hafeez, *Simulation of an Arterial Incident Environment with Probe Reporting Capability.* Transportation Research Record: Journal of the Transportation Research Board, 1998. 1644(-1): p. 116-123.

66. Yang, X. and W. Recker, *Evaluation of Information Applications of a Self-Organizing Distributed Traffic Information System for a Large-Scale Real-World Traffic Network.* Computer-Aided Civil and Infrastructure Engineering, 2008. 23(8): p. 575-595.

67. Srinivasan, K.K. and P.P. Jovanis, *Determination of Number of Probe Vehicles Required for Reliable Travel Time Measurement in Urban Network.* Transportation Research Record: Journal of the Transportation Research Board, 1996. 1537(-1): p. 15-22.

68. Quiroga, C.A. and D. Bullock, *Determination of Sample Sizes for Travel Time Studies.* ITE Journal, 1998. 68(8): p. 92-98.

69. Boyce, D., *A Memoir of the ADVANCE Project.* ITS Journal (Intelligent Transportation Systems), 2002. 7(2): p. 105-130.

70. Sen, A., et al., *Estimation of Static Travel Times in a Dynamic Route Guidance System - II*. Mathematical and Computer Modelling (Oxford), 1998. 27(9-11): p. 67.

71.Guhnemann, A., et al., *Monitoring Traffic and Emissions by Floating Car Data*. 2004, Institute of Transport Studies: Sydney. p. 17.

72. Chen, M. and S.I.J. Chien, *Determining the Number of Probe Vehicles for Freeway Travel Time Estimation by Microscopic Simulation.* Transportation Research Record: Journal of the Transportation Research Board, 2000. 1719(-1): p. 61-68.

73. Torday, A. and A.G. Dumont. *Link Travel Time Estimation with Probe Vehicles in Signalized Networks*. 2003.

74. Graves, T.L., A.F. Karr, and P. Thakuriah, *Variability of Travel Times on Arterial Links: Effects of Signals and Volume.* National Institute of Statistical Science (North Caroline) technical report, 1998.

75. He, R.R., et al., *Temporal and Spatial Variability of Travel Time.* Center for Traffic Simulation Studies, 2002.

76. Dia, H. and S. Panwai, *Modelling Drivers' Compliance and Route Choice Behaviour in Response to Travel Information. Special issue on Modelling and Control of Intelligent Transportation Systems.* Journal of Nonlinear Dynamics, 2007. 49(4): p. 493–509.

77. Chen, W.H. and P.P. Jovanis, *Driver EN Route Guidance Compliance and Driver Learning with Advanced Traveler Information Systems: Analysis with Travel Simulation Experiment.* Transportation Research Record: Journal of the Transportation Research Board, 2003. 1843(-1): p. 81-88.

78. Srinivasan, K.K. and H.S. Mahmassani, *Modeling Inertia and Compliance Mechanisms in Route Choice Behavior under Real-time Information.* Transportation Research Record: Journal of the Transportation Research Board, 2000. 1725(-1): p. 45-53.

79. Chen, P.S. and H.S. Mahmassani. *Reliability of Real-time Information Systems for Route Choice Decisions in a Congested Traffic Network: Some Simulation Experiments*. 1991.

80. Mahmassani, H.S. and P. Shen-Te Chen, *Comparative Assessment of Origin-based and En Route Real-time Information under Alternative User Behavior Rules.* In-vehicle information systems: modeling traffic networks and behavioral considerations, 1991, 1991. 1306: p. 69.

81. Mahmassani, H.S., *Dynamic Network Traffic Assignment and Simulation Methodology for Advanced System Management Applications.* Networks and Spatial Economics, 2001. 1(3): p. 267-292.

82. Ben-Akiva, M., et al. *Modeling Inter Urban Route Choice Behavior*. 1984: VSP Intl Science.

83. Lappin, J. and J. Bottom, *Understanding and Predicting Traveler Response to Information: a Literature Review*. US Department of Transportation, December, 2001.

84. Ben-Akiva, M. and T. Morikawa, *Estimation of Switching Models from Revealed Preferences and Stated Intentions.* TRANSP. RES., 1990. 24(6): p. 485-495.

85. Keith Yu Kit, L., et al. *Development of a Microscopic Traffic Simulator for Inter-vehicle Communication Application Research*. in *Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE*. 2006.

86. Jetcheva, J.G., et al. *Design and Evaluation of a Metropolitan Area Multitier Wireless Ad Hoc Network Architecture*. in *Mobile Computing Systems and Applications, 2003. Proceedings. Fifth IEEE Workshop on*. 2003.

87. Hormann, Y., et al. *Simulator for Inter-vehicle Communication Based on Traffic Modeling*. in *Intelligent Vehicles Symposium, 2004 IEEE*. 2004.

88. Eichler, S., et al. *Simulation of Car-to-car Messaging: Analyzing the Impact on Road Traffic*. 2005. Atlanta, GA, United States: IEEE Computer Society, Los Alamitos, CA 90720-1314, United States.

89. Wu, H., et al. *MDDV: a Mobility-centric Data Dissemination Algorithm for Vehicular Networks*. 2004: ACM New York, NY, USA.

90. Kim, H., Shin, M., Nam, B. Lovell, D. J., *An Integrated Transportation and Communication Simulation Framework for Vehicular Ad Hoc Network Applications*, in *TRB 2008 (87. Annual Meeting)*. 2008: Washington, DC (USA).

91. Widodo, A., Hasegawa, T. *Evaluations of Traffic Safety Improvement Using an Autonomous Traffic Flow Simulator Including Inter-vehicle Communications*. in *Global Telecommunications Conference 98*. 1998: IEEE.

92. Artimy, M.M., W. Robertson, and W.J. Phillips. *Vehicle Traffic Microsimulator for Ad Hoc Networks Research*. 2005. Oulu, Finland: Institute of Electrical and Electronics Engineers Computer Society, Piscataway, NJ 08855-1331, United States.

93. Mangharam, R., et al. *GrooveNet: A Hybrid Simulator for Vehicle-to-Vehicle Networks*. in *Mobile and Ubiquitous Systems: Networking & Services, 2006 Third Annual International Conference on*. 2006.

94. Eichler, S. *Performance Evaluation of the IEEE 802.11p WAVE Communication Standard*. in *Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th*. 2007.

95. Jiang, D. and L. Delgrossi. *IEEE 802.11 p: Towards an International Standard for Wireless Access in Vehicular Environments*. 2008.

96. PTV, P.T.V.A., *VISSIM 5.10 User Manual*. 2009.

97. Joo-Han, S., W.S.W. Vincent, and C.M.L. Victor, *A Framework of Secure Location Service for Position-based Ad Hoc Routing*, in *Proceedings of the 1st ACM international workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*. 2004, ACM: Venezia, Italy.

98. PTV, A.P.T.V., *VISSIM 4.20 User Manual*. 4.20 ed. 2006, Karlsruhe: PTV.

99. Burghout, W. and J. Wahlstedt. *Hybrid Traffic Simulation with Adaptive Signal Control*. in *TRB annual meeting*. 2007. Washington D.C.: TRB.

100. Balke, K., C.L. Dudek, and C.E. Mountain, *Using Probe-measured Travel Times to Detect Major Freeway Incidents in Houston, Texas.* Transportation Research Record: Journal of the Transportation Research Board, 1996. 1554(-1): p. 213-220.

101. Mahmassani, H.S. and R. Jayakrishnan, *System Performance and User Response under Real-time Information in a Congested Traffic Corridor*. Transportation research. Part A: general, 1991. 25(5): p. 293-307.

102. Von Tomkewitsch, R., *Dynamic Route Guidance and Interactive Transport Management with ALI-SCOUT.* IEEE Transactions on Vehicular Technology, 1991. 40(1 Part 2): p. 45-50.

103. Enkelmann, W. *FleetNet - Applications for Inter-vehicle Communication*. in *Intelligent Vehicles Symposium, 2003. Proceedings. IEEE*. 2003.

104. Wu, H., et al., *Efficiency of Simulated Vehicle-to-Vehicle Message Propagation in Atlanta, Georgia, I-75 Corridor.* Transportation Research Record: Journal of the Transportation Research Board, 2005. 1910(-1): p. 82-89.

105. Wahle, J., et al., *Decision Dynamics in a Traffic Scenario.* Physica A: Statistical Mechanics and its Applications, 2000. 287(3-4): p. 669-681.

106. Bazzan, A.L.C., et al., *To Adapt or Not to Adapt--Consequences of Adapting Driver and Traffic Light Agents.* Lecture Notes in Computer Science, 2008. 4865: p. 1.

107. Hawas, Y.E. and H.S. Mahmassani, *Comparative Analysis of Robustness of Centralized and Distributed Network Route Control Systems in Incident Situations.* Transportation Research Record: Journal of the Transportation Research Board, 1996. 1537(-1): p. 83-90.

108. Chiu, Y.C. and H.S. Mahmassani, *Hybrid Real-time Dynamic Traffic Assignment Approach for Robust Network Performance.* Transportation Research Record: Journal of the Transportation Research Board, 2002. 1783(-1): p. 89-97.

109. Chiu, Y.C. and H.S. Mahmassani, *Routing Profile Updating Strategies for Online Hybrid Dynamic Traffic Assignment Operation.* Transportation Research Record: Journal of the Transportation Research Board, 2003. 1857(-1): p. 39-47.

110. Choffnes, D.R. and F.E. Bustamante. *An Integrated Mobility and Traffic Model for Vehicular Wireless Networks*. 2006. Cologne, Germany: Association for Computing Machinery, New York, NY 10036-5701, United States.

111. Blum, J., A. Eskandarian, and L.J. Hoffman. *Performance Characteristics of Inter-vehicle Ad Hoc Networks*. in *Intelligent Transportation Systems, 2003. Proceedings. 2003 IEEE*. 2003.

112. Liu, Y., U. Ozguner, and T. Acarman, *Performance Evaluation of Inter-vehicle Communication in Highway Systems and in Urban Areas.* IEE Proceedings: Intelligent Transport Systems, 2006. 153(1): p. 63-75.

113. DOT. *IntelliDriver-Safer, Smarter, Greener*. 2009 [cited 2009 12/30/2009]; Available from: http://www.intellidriveusa.org/.